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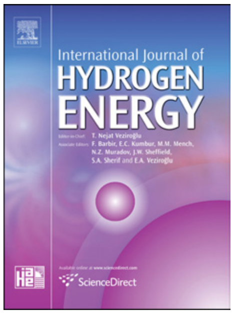

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Highlights

- The Froude number only based correlations are not applicable to under-expanded jets.
- The novel correlation for hydrogen jet flame length accounts for Fr, Re, M effects.
- Three fire regimes: buoyancy, momentum expanded, momentum under-expanded jets.
- Concentration in unignited jet 11% not 29.5% matches the location of jet flame tip.
- Conservative separation distances for jet fire are longer than for non-reacting jet.

HYDROGEN JET FLAMES

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ABSTRACT

A critical review and rethinking of hydrogen jet flame research is carried out. Froude number only based correlations are shown to be deficient for under-expanded jet fires. The novel dimensionless flame length correlation is developed accounting for effects of Froude, Reynolds, and Mach numbers. The correlation is validated for pressures 0.1-90.0 MPa, temperatures 80-300 K, and leak diameters 0.4-51.7 mm. Three distinct jet flame regimes are identified: traditional buoyancy-controlled, momentum-dominated "plateau" for expanded jets, and momentum-dominated "slope" for under-expanded jets. The statement "calculated flame length may be obtained by substitution the concentration corresponding to the stoichiometric mixture in equation of axial concentration decay for non-reacting jet" is shown to be incorrect. The correct average value for non-premixed turbulent flames is 11% by volume of hydrogen in air (range 8%-16%) not stoichiometric 29.5%. All three conservative separation distances for jet fire are shown to be longer than separation distance for non-reacting jet.

KEYWORDS: hydrogen safety engineering; under-expanded jet theory; jet flame length; the similarity law; dimensionless correlation; flame tip location

1. INTRODUCTION

The use of hydrogen and fuel cell systems at pressure up to 100 MPa brings new engineering challenges to provide public safety through carrying out hydrogen safety engineering. The hydrogen safety engineering is defined as an application of scientific and engineering principles to the protection of life, property and environment from adverse effects of incidents/accidents involving hydrogen. To formulate the principles of hydrogen safety engineering a proper understanding of underlying physical phenomena is needed including unignited releases and dispersion, spontaneous ignition and jet fires, deflagrations and detonations, etc.

This work is aiming to look at scientific and engineering principles for hydrogen jet fires based on the critical analysis of previous research and the analytical scrutiny of unique experimental data on high pressure hydrogen jet flames generated recently within the international hydrogen safety community (http://www.hysafe.org/IAHySafe).

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Safety is often mistakenly called a “non-technical” barrier to the emerging hydrogen economy. In fact, the hydrogen safety is a challenging area of science and engineering, technological development and innovation. There is a number of demanding engineering issues to be resolved before rolling out hydrogen and fuel cell technologies to the market. These unresolved issues include but not limited to the reduction of the under-expanded jet flame length from current 10-15 m from the hydrogen-powered vehicle onboard storage to allow evacuation of passengers and their safeguarding by first responders when relevant. Another important safety issue to be addressed by car manufacturers is the increase of fire resistance rating of onboard storage tanks from present 1-7 minutes for type 4 vessels to allow longer time for blow-down of tanks. This in turn would prevent severe destruction of civil structures like garages during accidental release, and exclude even a potential for formation of large hydrogen-air clouds in tunnels able to make fatalities throughout the whole length of the tunnel. Higher fire resistance rating on hydrogen storage tanks would permit safe evacuation of civilians from the accident scene, etc.

One of challenges for safety engineering is determination of science-informed separation distance from a hydrogen system. The separation distance can be defined, based on [1], as the minimum separation between a hazard source and an object (human, equipment or environment) which will mitigate the effect of a likely foreseeable incident and prevent a minor incident escalating into a larger incident/accident. The following definitions can be used to distinguish between incident and accident. Incident is something that occurs casually in connection with something else, and accident is an unforeseen and unplanned event or circumstance causing loss or injury.

Depending on incident scenario the minimum separation distance could be determined either by characteristics of an unignited release, or parameters of a jet fire, or pressure effects from deflagration and detonation. This study addresses the question which of the separation distances, i.e. based on hazards from non-reacting jet (unignited leak) or hazards from reacting hydrogen release (jet flame), from the same source is longer. Only free jets are considered in this study.

Hydrogen jets from storage tanks and equipment at pressures up to 100 MPa will be mainly in a form of under-expanded jet. The under-expanded jet is defined as a jet with pressure at the nozzle exit is above the atmospheric pressure. Unfortunately, under-expanded hydrogen flames can reach tens of meters from current pressure relief devices for onboard storage of hydrogen-fuelled vehicles, and up to hundreds of meters for large diameter high pressure industrial hydrogen pipes. This raises an important issue of a link between safety and cost-effectiveness of new technology applications through reduction of separation distances by the engineering design.

The prediction of laminar and turbulent non-premixed hydrogen jet flame length has been the subject of studies starting from the seminal work of Hawthorne et al. [2]. Analysis of previous research shows that practically all former correlations of the dimensionless flame length, i.e. the flame length normalized by the burner nozzle diameter, are based on the Froude number (*Fr*) in one or another form. This statement is applicable to both former works mainly on expanded jets and recent studies on highly under-expanded jets. It is quite obvious that *Fr*-based correlations, ignoring theoretically predicted and experimentally proved dependence on Reynolds (*Re*) and Mach (*M*) numbers, cannot be of general nature in a wide range of parameters.

The former correlations distinguish two regimes of jet fires. The first regime is buoyancy-controlled jet fire. This regime is characterised by lower *Fr*, and the dimensionless flame length, L_F/D, where L_F is the flame length and D is the nozzle exit diameter, grows with *Fr* number. The second regime is momentum-dominated jet flame. This regime is characterised by larger *Fr* numbers compared to the buoyancy-controlled regime. The dimensionless flame length is independent of *Fr* for momentum-dominated jet flames. It is worth noting that this was derived for expanded jets only. This study expands the current classification of jet fires to include under-expanded jet fires through the development of a novel correlation for jet fires that comprises dependence on *Fr*, *Re* and *M* numbers.

Jet fire is a typical scenario for hydrogen accidents. Statistics proves that in the most situations unscheduled hydrogen release will be ignited [3]. Knowledge of the jet flame length and related separation distances is of key importance for hydrogen safety engineering. In 1957 Sunavala et al. [4] stated that ”calculated flame length may be obtained by substitution the concentration corresponding to the stoichiometric mixture in equation of axial concentration decay for non-reacting jet”.

The statement was reiterated not once in later studies. For instance, in 1975 Bilger and Beck [5] “for convenience” defined the flame length as the length on the axis to the point having a mean composition which is stoichiometric (hydrogen concentration is twice of oxygen). In 1976 Bilger [6] repeated that, for reaction rates limited by diffusion, the pioneering work of Hawthorne et al. [2] showed that the flame problem is analogous to an equivalent non-reacting mixing problem with the reaction zone appearing at the contour, where the nozzle fluid concentration has been diluted to stoichiometric.

However, these statements can be questioned if the Hawthorne’s concept of the concentration fluctuations in turbulent flame or local “unmixedness”, producing a statistical smearing of reaction zone and a consequent lengthening beyond the point where the mean composition of mixture is stoichiometric, is applied. Indeed, our preliminary study [7] and conclusions of this complete work demonstrate that hydrogen non-premixed turbulent jet flame tip is located much farther from the nozzle as will be shown below, i.e. from 2.2 times (for shortest flame limit of 16% by volume of hydrogen in air mixture) to 4.7 times (for longest flame limit of 8%), compared to the axial location of stoichiometric concentration of hydrogen in air in non-reacting momentum-dominated jet. The existing misinterpretations of the hydrogen flame length based on former studies could have serious safety and economical implications and will be clarified by this work.

This paper starts from a critical chronological overview of research on hydrogen jet flames. The rethinking of experimental data and different hydrogen jet flame length correlations is undertaken. The investigation into the location of the hydrogen jet flame tip and matching distance to axial concentration in non-reacting jet from the same leak source is carried out. The under-expanded jet theory is described that is applied to calculate parameters of under-expanded jets at the nozzle exit used in the flame length correlations.

The ultimate goal of this study is the advancement of hydrogen jet flames understanding and the development of reliable tools for hydrogen safety engineering, including a general dimensionless correlation for predicting the length of expanded and under-expanded hydrogen jet flames from round nozzles of arbitrary size at different storage pressures and temperatures.

2. CHRONOLOGICAL OVERVIEW OF HYDROGEN JET FLAME RESEARCH

Hawthorne et al. [2] had concluded at their seminal study on expanded hydrogen flames that the flame length, L_F, is proportional to the nozzle diameter, D, only. The fuel gas flow rate was found to have no effect on flame length as long as it is great enough to produce a fully developed turbulent flame. The following equation describing the dimensionless length of free turbulent flame jets was derived [2]

$$\frac{L_F - s}{D} = \frac{5.3}{C_{st}} \sqrt{\frac{T_{ad}}{\alpha_T T_N}\left[C_{st} + (1 - C_{st})\frac{M_S}{M_N}\right]}, \qquad (1)$$

where s is the distance from the breakpoint to the nozzle **[**8**]** (see Fig. 1), α_T is the ratio of reactant moles to product moles for stoichiometric mixture, T_{ad} is the adiabatic flame temperature, T_N is the temperature of fluid in the nozzle, C_{st} is the mole fraction of the nozzle fluid in stoichiometric mixture with air and M_S/M_N is the ratio of molecular masses of the surrounding and nozzle fluids.

<Figure 1 is here>

Equation (1) computes L_F/D=152 for a free turbulent hydrogen flame in air with parameters [2]: α_T =1.173, T_{ad}/T_N=8.04, C_{st}=0.296, M_S/M_N=14.45. Two experiments with vertical subsonic hydrogen jet fire were reported [2]. Each experiment was repeated in a darkened and lit room. The first experiment consisted of a rounded nozzle of 4.76 mm diameter with L_F/D=134 in a lit room (Re=2,870; $Fr=U_N^2/gD$=92,000, where U_N is the velocity in the nozzle and g is the acceleration due to gravity; the flame width to length ratio was reported as W_F/L_F =0.21). The second experiment investigated a sharp-edged nozzle orifice of 4.62 mm diameter with L_F/D=147 (Re=3,580; Fr=158,000). The visible flame length observed in the darkened room was 10% greater than that observed in the lit room [2].

To distinguish between purely diffusion flames, when flow from a burner is laminar, and turbulent flames from the same burner the last are called here turbulent non-premixed flames following the established terminology. Figure 1 shows progressive change of the flame height with the nozzle velocity during transition from laminar diffusion to fully developed turbulent non-premixed flame as observed in study [2]. In the beginning the increase of nozzle velocity leads to the increase of flame length for laminar flames. Then, at some velocity the laminar flame height reaches its maximum and starts to decline as the flame becomes turbulent at its tip first. The transition from vertical laminar diffusion flame to turbulent flame starts to occur at Reynolds number of around Re=2000 when considering the release of hydrogen into still air. Finally, Hawthorne et al. [2] concluded, based on their experiments with expanded jets, that fuel gas flow rate has no effect on the flame length as long as it is great enough to produce a fully developed turbulent flame.

Hawthorne et al. [2] pointed out that it does not follow that burning will proceed as far as ideal mixing would allow since actually the sample has a rapid time variation in constitution so that excess oxygen and excess hydrogen can alternate to produce a mixture capable of further combustion [2], [9]. They showed as well that the actual variation of hydrogen concentration (normalised by axial concentration) over a cross-section of jet fire (normalised by a jet width where concentration is half of maximum concentration) is independent of distance from the nozzle. This result can be used for verification of computational fluid dynamics (CFD) simulations of expanded jet fires.

It is not obvious that conclusions of study [2] on expanded jet fires, especially about independence of flame length on the nozzle velocity for turbulent, can be expanded to under-expanded jet fires. For instance, the turbulence and velocity fluctuation at the under-expanded jet axis downstream of the Mach disk is known to be quite high compared to sub-sonic flows, i.e. the ratio of root mean square (r.m.s.) to average axial velocity is 0.25±10% as derived in 1953 by Thring and Newby [9] from experiments of Corrsin [10]. This high level of turbulence in under-expanded jets has been confirmed recently by the application of the large eddy simulation (LES) technique [11] to process experimental data on jet fires by Sandia National Laboratories.

In 1972 Golovichev and Yasakov theoretically predicted the maximum flame length to nozzle diameter ratio L_F/D=220 [12]. The maximum measured value for a subsonic release, i.e. expanded jet, was L_F/D=205 at velocity 365 m/s.

In 1974 the first systematic attempt to investigate flame length over the whole applicable range of operation from forced convection (jets) to natural convection (plumes) was undertaken by Baev and colleagues [13],[14], as stated by Becker and Liang [15]. The basic flame length equation derived by these studies resembles that of Hawthorne et al. [2] but is more general in that it allows for effects of compressibility (Mach number) [15]. More than 70 experiments were performed with nozzle diameters ranging from 1 mm to 16.65 mm, investigating both subsonic and supersonic jets with Mach number from 0.25 to 3.08 (outflow velocities up to 2600 m/s).

Experimental error was ±15%. In spite of the understanding of the role of *Fr, Re, M* numbers, the experimental flame length data were presented as a function of the Froude number $Fr=U_N^2/gD$ only, similar to the approach used for the first time to our knowledge by Shorin and Ermolaev [16] in 1952.

Baev et al. [13] theoretically derived that at the momentum-controlled limit the flame length $L_F \sim Re$, or dimensionless flame length $L_F/D \sim U_N\rho/\mu$, where ρ is the gas density and μ is the viscosity. This means that the dimensionless flame length, L_F/D, has to be a constant for sonic (choked) expanded jets if both the density and the viscosity remain unchanged. In the presence of lifting (buoyancy) forces they derived that $L_F \sim Re^{2/3}Fr^{1/3} \sim u^{4/3}D^{1/3}$. The largest experimental ratio L_F/D=230 was observed for subsonic flow [13].

In the same year 1974 Baev and Yasakov [14] showed theoretically that depending on *Fr* there will be a characteristic peak in $L_F(Re)$ function, mentioned by Hottel and Hawthorne **[8]**, or there will be no peak for nozzles of larger diameter (Fig. 2).

<Figure 2 is here>

They derived within the assumptions of their theory that the ratio of maximum laminar to maximum turbulent flame length is L_l/L_t=1.74 and is independent of fuel type [14]. This ratio decreases with the increase of diameter *D* (see Fig. 2). There is a critical diameter above which the flame length in a whole range of *Re* is below the value L_t. They suggested that the limit of turbulent flame length L_t can be reached at $Re \to \infty$. The relationship $\mathrm{Re}^2 = Fr \cdot D^3 \cdot g / \nu^2$ was used in their discussion about the turbulent limit for jet fire length L_t. The experimental data [14] gives a maximum L_F/D=230 for laminar jet flames and a limit L_F/D=190 for turbulent jet fires.

Three years later in 1977 the theoretical conclusions by Baev et al. [13],[14] were confirmed by experiments of Schevyakov and Komov [17] (Fig. 3).

<Figure 3 is here>

In 1974 Lavoie and Schlader [18] published the experimental study from which information on flame length for the momentum-controlled regime can be extracted partially. All tests were performed at constant *Re*=4500. Two of four experiments were performed within the momentum-controlled limit: *D*=0.48 mm ($Fr=1.6 \cdot 10^8$), *D*=0.96 mm ($Fr=2.1 \cdot 10^7$). Other two tests were in the transitional area closer to the momentum-controlled limit: *D*=2.2 mm ($Fr=1.8 \cdot 10^6$), *D*=3.3 mm ($Fr=5.0 \cdot 10^5$). The length was estimated by the most remote location of flame sampling (*x/D*=200, except *x/D*=180 for nozzle *D*=3.3 mm). Thus, actual flame lengths can be a bit longer.

In 1975 Bilger and Beck [5] conducted experiments with vertical jet diffusion hydrogen flame at constant *Fr* so that fluid dynamics similarity is obtained. They carried out the study using a principle of fluid dynamics stating that a jet issuing into still surroundings will exhibit main flow similarity independent of viscosity if the Reynolds number based on jet diameter and velocity at exit is sufficiently high. This phenomenon was called by Townsend “Reynolds number similarity” [19]. Bilger and Beck highlighted that the flames should exhibit Reynolds number similarity if the Froude number, the nozzle fluid density and composition are kept constant. Only three experiments were carried out for measurements of flame length dependence on the Froude number with Fr=0.6·10^6, 1.5·10^6, and 5.2·10^6. There is an indication of the flame length saturation for Fr above 1.5·10^6 in their experiments.

However, the flame length “for convenience” was defined mistakenly (from our point of view) as the length on the axis to the point having a mean composition which is stoichiometric (hydrogen concentration is twice of oxygen) [5]. No experimental data on actual flame lengths was reported. Authors of [5] did not give details on how visible flame lengths in Hawthorne et al. study [2], i.e. L_F/D=134 and 147, were transformed into “stoichiometric hydrogen/oxygen flame length” of about 79 and 89 respectively. If the same ratio (134/79=1.69) was applied to the momentum-dominated limit of the dimensional flame length associated with Lavoie and Schlader experiments [18] (in Fig. 8 from paper [5]), then the value L_F/D =125·1.69=212 for visible flame length could be derived from the Bilger and Beck’s paper [5]. Bilger and Beck noted as well that the experiments of Lavoie and Schlader [18] were made for constant jet Reynolds number and exhibit no basic similarity due to the variation of the Froude number.

In 1976 Bilger [6] stated, with reference to the pioneering work of Hawthorne et al. [2], that for reaction rates limited by diffusion the flame problem is analogous to an equivalent non-reacting mixing problem with the reaction zone appearing at the contour, where the nozzle fluid concentration has been diluted to stoichiometric. It is not clear laminar or turbulent diffusion was mentioned. This statement contradicts to a conclusion of present study that the flame tip is located farther downstream of the location of the stoichiometric concentration in a non-reacting turbulent jet from the same leak source. It is thought that the conclusion of our study is in line with the Hawthorne et al.’s concept [2] of concentration fluctuations in turbulent non-premixed flame or local “unmixedness”, producing a statistical smearing of reaction zone and a consequent lengthening beyond the point where the mean composition of mixture is stoichiometric.

In 1977 Shevyakov, whose group’s studies of hydrogen non-reacting and reacting jets are barely known and thus not cited in English literature on the subject, had published with Komov probably the only paper translated into English [17]. Shevyakov et al. reported more results on unignited hydrogen jets in paper [20], and for jet fires in [21] both published in Russian. The experimental dependence of L_F/D on Re up to Re=20,000 is presented in study [17] for nine stainless steel tubular burners of diameter 1.45-51.7 mm (reproduced in Fig. 3). Burner length to diameter ratio was changing from 50 for smaller diameter burners to 10 for the largest one. The visual length of on-port subsonic flames was measured in a darkened room. The hydrogen density of 0.0899 kg/m^3 and the temperature of 273 K were assumed in the nozzle exit during the processing of the Shevyakov’s data in this study.

The experimental dependence of L_F/D on *Re* for smaller diameter (below 6 mm) burners has a characteristic peak [17] predicted theoretically by Baev et al. [13] (see Figs. 2 and 3). This peak magnitude is decreasing with increase of burner diameter in the area of transition from laminar to turbulent flow (Re<2,300). Then L_F/D increases with *Re* approaching a limit L_F/D=220-230 at high Reynolds numbers. This is above a turbulent jet flame limit L_F/D=190 measured by Baev and Yasakov [14] (similar value L_F/D=230 was measured by Baev et al. for laminar jet flames). For the same Reynolds number L_F/D decreases with the diameter increase (see Fig. 3).

Shevyakov et al. [17],[20] carried out and summarised in coordinates L_F/D versus $Fr=U_N^2/gD$ probably the largest number of experiments on subsonic hydrogen jet fires in still air (more than 70). The momentum-dominated limit L_F/D=220-230 for subsonic hydrogen jet fires was reached at $Fr>2\cdot10^6$. This limit is substantially above the value L_F/D=152 reported by Hawthorne et al. [2]. In spite of the difference between these numbers there is no contradiction. Indeed, two experiments reported by Hawthorne et al. [2] were performed with nozzle diameters 4.62 mm and 4.76 mm (Re=2,870 and 3,580 respectively) and were in buoyancy-controlled flow regime. For similar experimental conditions, i.e. nozzle diameter and velocity, the dimensionless flame length in Hawthorne et al. [2] tests is practically exactly reproduced in Shevyakov et al. study [20] as will be demonstrated in more detail below.

Probably the most validated correlation for calculation of the dimensionless flame length of vertical subsonic hydrogen jet fires is developed by Shevyakov et al. [17], [21]. The correlation is in coordinates L_F/D versus $Fr=U_N^2/gD$ and covers the range of conditions from buoyancy-controlled (lower *Fr*) to momentum-dominated (higher *Fr*) subsonic hydrogen jet flames.

To account for the conservative increase of the momentum-dominated limit from L_F/D=220 in study [17] to L_F/D=230 in work [21], and to achieve continuous piecewise linearity of the correlation in the whole range of *Fr* the following modification of the original correlation [17] has been obtained here using linear regression analysis

$$
\begin{aligned}
&L_F / D = 15.8 \cdot Fr^{1/5}\ (Fr < 10^5);\\
&L_F / D = 37.5 \cdot Fr^{1/8}\ (10^5 < Fr < 2\cdot 10^6);\\
&L_F / D = 230\ \ (Fr > 2\cdot 10^6).
\end{aligned}
\tag{2}
$$

This correlation can be used to explain the "scattering" of experimental data on L_F/D measured by different authors. For example, experimental value L_F/D=147 by Hawthorne et al. [2] is substantially below the experimental limit L_F/D=230 established in work [21]. Nevertheless, these results are in agreement. Indeed, the substitution of *Fr* from two experiments by Hawthorne et al. [2] into correlation (2) gives L_F/D=152 for rounded nozzle (experimental Fr=92,000; measured in the illuminated room L_F/D=134 [2]), and L_F/D=164 for sharp-edged nozzle orifice (Fr=158,000; measured L_F/D=147 [2]). The correlation (2) overestimates the measured values of L_F/D by 15%. This is of the same order of magnitude as 10% difference in hydrogen flame length measured in lit and darkened room.

The comparison between the Shevyakov's correlation (2) at the momentum-controlled limit and the similarity law for concentration decay in non-reacting expanded jets [22] has revealed recently [7] that the concentration of hydrogen in a non-reacting expanded jet at a distance equal to the flame tip location is about 8.5% by volume. This is "surprisingly" close to the flammability limit of 8.5-9.5% for downward and spherically propagating premixed hydrogen-air flames. This result [7] contradicts to previously published point of view [4],[5],[6] that the flame length may be calculated by substitution of the concentration corresponding to the stoichiometric mixture (29.5% by volume of hydrogen in air) into the equation of axial concentration decay for non-reacting jets.

In 1978 Becker and Liang [23] validated previous findings by Baev et al. [13],[14] and Shevyakov et al. [17] that under the natural convection conditions (buoyancy-controlled regime) flames of large base diameter are found to be rather short (smaller L_F/D compared to the momentum-dominated limit, see Figs. 2 and 3). This observation was used by authors to explain the behaviour of large pan fires of Blinov and Khudyakov [24]. They stated that flames in the forced convection limit are around 50% longer than previously suspected for subsonic releases. By this reasoning they increased the coefficient in Eq. (1) by Hawthorne et al. [2] from 5.3 to 11 (more than 100% increase of the flame length). Hydrogen of comparatively low 99% by volume purity was used in their experiments, despite the fact that presence of hydrocarbons can strongly affect hydrogen combustion in air [25]. In fact, it is known that in the momentum-controlled regime the flame length of hydrocarbons is longer: methane jet flame is about 130% of hydrogen jet flame length, and propane is 200% [26].

Becker and Liang [23] developed the overall flame length model and gave general correlations for predicting flame length for the whole range of operations from full forced convection to full natural convection. The correlations are built on the Richardson number, *Ri*, which in thermal convection problems represents the importance of natural convection relative to the forced convection. The characteristic source momentum flux was embedded into *Ri*.

In 1984 Kalghatgi [27] published experimental data of more than 70 tests with nozzle diameters in the range 1.08-10.1 mm, both with subsonic and sonic hydrogen jet flames. The maximum measured flame lengths agree well with the modified correlation of Shevyakov (2). However, all data are below that recommended by the Becker and Liang formula [23]. Kalghatgi undoubtedly stated that his results disagree with the Becker and Liang's predictions.

The original experimental data [27] are reproduced in Fig. 4. Two conclusions can be drawn from Kalghatgi's experimental study. Both conclusions are valid for subsonic and sonic flows: 1) flame length grows with the mass flow rate at fixed diameter (D=const), and 2) flame length grows with the diameter at fixed mass flow rate ($\dot{m}$=const). These conclusions put under doubt the generality of the statement by Hawthorne et al. [2], made by the analysis of subsonic jets only, that flame length is proportional to nozzle diameter only and hydrogen flow rate is not a factor.

Moreover, conclusions [27] can be used to question the generality of recent correlation of the flame length with the mass flow rate only [28] that obviously ignores the revealed by Kalghatgi dependence on the nozzle diameter at $\dot{m}$ =const.

Kalghatgi also showed [27] that the lift-off height varies linearly with the jet exit velocity and is independent of the burner diameter for a given gas.

<Figure 4 is here>

The dependence of flame height on mass flow rate implies that non-ideal behaviour of hydrogen at high pressures should be accounted for in the development of jet flame length correlations. In this study we assume that hydrogen temperature in a storage tank of the Kalghatgi's experimental set-up [27] was 273 K and the density in nozzles for subsonic flows was 0.0899 kg/m^3. For under-expanded jets [27] the initial temperature in the container was assumed to be the same, i.e. 273 K, and the density of hydrogen at the nozzle exit was calculated using the under-expanded jet theory [29].

In 1993 Delichatsios [30] studied flame height relationships in the range from buoyancy- to momentum-controlled turbulent non-premixed expanded jet flames. The "fire Froude number" for reacting flows similar to Ricou and Spalding [31] was applied. For the momentum-dominated limit it was suggested that L_F/D=23(S+1)$(\rho_N/\rho_S)^{1/2}$, where S is the air to fuel mass stoichiometric ratio. This gives the maximum value of L_F/D=210 for expanded hydrogen jets into still air (S=33.72), that is somewhat below the value L_F/D=220-230 published sixteen years earlier [17].

In 1993 Blake and McDonald [32] showed that for upward turbulent diffusion flames the dimensionless flame length L_F/D is a function of a density weighted Froude number (inverse Richardson number) and a flame density to ambient density ratio. Authors commented that in the momentum-controlled limit, the length of horizontal flame is identical to the length of vertical flame from the same source. While in the buoyancy limit, the vertical size of a horizontally directed jet flame approaches the length of a vertical flame.

In 1998 Cheng and Chiou [33] observed that an increase of the lift-off velocity increases the lift-off height without significantly altering the hydrogen flame height. For example, an increase of lift-off velocity from 530 to 1120 m/s for a nozzle of 1.8 mm diameter increases the flame height from 37 to 49 cm.

In 1999 Heskestad published a paper [26] on "consolidation of flame height data for turbulent jet diffusion flames". Assuming subsonic discharge, Heskestad concluded that the momentum-controlled limit for hydrogen is L_F/D=175. Unfortunately, this limit is below the limit L_F/D=220-230 established by Baev et al. and Shevyakov et al. in 1974-1977 and confirmed in present study.

In 2005 Mogi et al. [28] demonstrated experimentally (horizontal hydrogen jet flames from convergent nozzles of 0.1-4 mm diameter in the range of overpressures 0.01-40 MPa were studied) that the dimensionless flame length increases with the spouting pressure (static pressure measured close to nozzle exit) as $L_F/D=524.5 \cdot P^{0.436}$, where pressure P is in MPa. This experimental correlation implies that the momentum-controlled "plateau" should have extremely large scattering of experimental data if the coordinates L_F/D versus Fr to be used as in previous studies for expanded jets. The correlation [28] gives for subsonic flows the maximum $L_F/D=254$ (at the spouting pressure 0.19 MPa), which is slightly above the maximum value $L_F/D=230$ obtained previously for expanded jets.

The ratio L_F/D becomes extremely high at 70 MPa, i.e. $L_F/D=3344$ [28]. Convergent nozzles are characterised by smaller hydraulic losses and consequently larger flame lengths can be expected. The nozzle in study [28] was positioned 1 m above a floor and 1 m from a wall. The proximity of a jet to the floor and/or wall can affect the flame length due to the change in air entrainment. It is well known that fire plume along a wall has longer axial decay of temperature with distance from the source compared to free plume. Increase of a hydrogen jet flame length up to 1.8 times, when released along a ground, has been observed recently in experiments [34]. The effect of a surface, along which the jet is released, on the concentration decay in the jet is not yet fully studied and formalised through an engineering correlation.

Under-expanded jet flames cannot be self-sustained at some conditions. For example, no stable flames were observed in study [28] for nozzle diameters 0.1 and 0.2 mm – flame blew off although the spouting pressure increased up to 40 MPa.

Mogi et al. [28] suggested that the flame length is proportional to the mass flow rate as $L_F=20.25 \cdot \dot{m}^{0.53}$ regardless of the nozzle diameter. However, it is easy to see from Fig. 5 in paper [28] that experimental data attributed to different nozzle diameters are distributed in exactly the same manner as in Kalghatgi's work [27].

In 2006 Schefer et al. [35] studied open-flame hydrogen vertical jets for both subsonic and sonic (choked) flows at pressures up to 17.2 MPa. They confirmed Kalghatgi's conclusion [27] that flame length increases with mass flow rate and jet nozzle diameter. Two sets of jet flame data are presented [35]: subsonic laboratory scale hydrogen releases (Fr from transitional $4.1 \cdot 10^5$ to momentum-controlled $6.5 \cdot 10^6$, Re from laminar 1569 to turbulent 6247) from a 1.91 mm diameter nozzle; and a blow-down test at an initial pressure of 17.2 MPa through a stainless steel tubing of 7.94 mm diameter ($Fr=2.6 \cdot 10^6$-$1.9 \cdot 10^7$, turbulent $Re=(1.9$-$9.8) \cdot 10^5$). It is worth noting that there was a 3.175 mm internal diameter manifold near the cylinder outlets to a 7.6 m straight section tubing of 7.94 mm diameter. This set-up could have reduced flame length due to pressure losses in the flow pathway.

The blow-down time of two cylinders of 49 litres each was about 100 s [35]. An attempt was made to present data for both expanded and under-expanded jet fires in coordinates "dimensionless flame length" versus "Froude number". Dimensionless flame length was defined by Schefer et al. [35] in a manner similar to Delichatsios [29] as $L^* = L_F \cdot f_S / D^*$, where the jet momentum diameter is $D^*=D_j(\rho_e/\rho_S)^{0.5}$, ρ_e/ρ_S is the ratio of jet gas density to ambient gas density, D_j is the jet exit diameter, and f_S is the mass fraction of fuel at stoichiometric conditions. The Froude number form employed was

$$Fr_f = \frac{U_e\, f_S^{3/2}}{(\rho_e/\rho_S)^{1/4}[(\Delta T_f/T_S)gd_j]^{1/2}} \quad , \tag{3}$$

where U_e is the jet exit velocity, ΔT_f is the peak flame temperature rise due to combustion heat release, and T_S is the ambient air temperature. The momentum-dominated regime is defined as $L^*=23$ ($Fr_f > 5$). Unfortunately, only limited number of experimental data was processed to validate the correlation [35].

Infrared, visible, and ultraviolet flame lengths were found to be related through the following equations $L_F/L_{IR}=0.88$, $L_F/L_{UV}=0.78$ [35]. For turbulent jet flames the flame width was assessed as $0.17 \cdot L_F$ that is somewhat narrower than $0.21 \cdot L_F$ in the study by Hawthorne et al. [2].

Later in 2007 Schefer et al. [36] published results of experiments with a nozzle diameter of 5.08 mm at higher pressures up to 41.3 MPa, where departures from ideal gas behaviour become more evident. Authors stated that lower-pressure engineering correlations for dimensionless flame length based on *Fr* apply to pressures up to 41.3 MPa, if the notional nozzle diameter and flow properties at the notional nozzle exit were substituted into the *Fr*-based correlation and non-ideal behaviour is accounted for. The blow-down of two hydrogen storage tubes of 617 litres volume each at initial pressure of 41.3 MPa through the experimental hydraulic system, including stagnation chamber, with 5.08 mm nozzle at the exit took approximately 500-600 s.

Schefer et al. [36] were the first to calculate notional nozzle exit parameters taking into account the non-ideal behaviour of hydrogen at high pressures. Their approach is analogous to Birch et al. [37] and is based on the conservation of mass and momentum, assumes no viscous forces, the ambient pressure and uniform velocity profile across the notional nozzle, sonic (choked) flow at the jet exit from actual nozzle, and isentropic flow relations. The previous correlation for flame length [35] was expanded in study [36] and a new equation for the notional nozzle, $D_{eff}=D(\rho_N U_N/\rho_{eff} U_{eff})^{0.5}$, where "*N*" denotes actual nozzle exit parameters and "*eff*" effective (notional) nozzle parameters, was applied. It is important to note that flow properties at the notional nozzle exit were used to build the correlation for the flame length in the coordinates L^*-Fr_f.

In 2008 Imamura et al. [38] carried out a series of experiments to understand the thermal hazards of hydrogen jet flames and more specifically temperature field of hot currents in the downstream region. They used hydrogen release system composed of a hydrogen cylinder, a stop valve, a regulator, an air-operated ball valve and a nozzle located 1 m above the ground. Experiments investigated the dependence of flame shape on: nozzle diameter of 1, 2, 3 and 4 mm and spouting pressure of 0.5, 1.0, 1.5, 2.0, 2.5 and 3.0 MPa. The hydrogen flame was visualized by spraying NaCl aqueous solution. The spouting pressure was measured at the pressure transducer close to the nozzle. With the assumption of temperature in the container equal to 273 K, the under-expanded jet theory [29] was applied here to calculate flow parameters at actual nozzle.

In 2009 Proust et al. [39] published experimental results on horizontal hydrogen jet flame in the widest range of pressures 1-90 MPa and leak diameters 1, 2, 3 and 10 mm. They used a type 4 tank of 25 liters capacity with hydrogen being released horizontally 1.5 m above the ground via a 10 m long pipe with internal diameter 10 mm with a valve (opening time 0.1 s) just upstream of the nozzle, and ignited by a continuous propane-air burner. The system was installed in an open gallery of 12 m^2 cross-section and 80 m long. The pressure was measured at the head of the tank, the temperature - inside the tank using K-Type thermocouples, and the mass flow rate was deduced from a numerical weighting device where the tank was located. There were some doubts about the accuracy of the mass flow rate provided. By this reason the experimental data on pressure and temperature [39] were used here to calculate mass flow rate and other flow parameters at a nozzle exit by the under-expanded jet theory [29]. It is found that calculated mass flow rates are in an excellent agreement with the experimental ones.

In 2009 Studer et al. [40] published results of their experimental study of hydrogen jet fires. Hydrogen was stored in a 25 liter type 4 tank at 10 MPa and released horizontally through a 5 m long flexible pipe with internal diameter of 15 mm. The hydrogen was released 1.5 m above the ground and ignited immediately after release by an electric spark. Pressure and temperature were recorded in the pipe just prior to the nozzle but were not given in the publication [40]. Releases through orifices of diameter 4, 7 and 10 mm were studied. The experimental data on pressure history, jet flame length and time of sampling were published elsewhere [41]. The flow parameters at actual nozzle exit were calculated using the under-expanded jet theory [29] in assumption that hydrogen temperature in the tank was 273 K.

3. THE UNDER-EXPANDED JET THEORY

Most of previous studies on hydrogen jet flames were performed with expanded jets with exception of recent studies aiming to underpin safe introduction of hydrogen as an energy carrier. The most of leaks from high pressure hydrogen equipment will be in a form of under-expanded jet. The under-expanded jet is a jet with a pressure at the nozzle exit above the atmospheric pressure. To predict accurately parameters of a leak at storage pressures above 10 MPa non-ideal behaviour of hydrogen should be taken into consideration. The first notional nozzle model accounting for the non-ideal behaviour of hydrogen at high pressures was developed by Schefer et al. [36].

The alternative theory of under-expanded jet is applied in this study. It is published elsewhere for under-expanded jets without losses [29], and for under-expanded jets with minor and friction losses [42]. Figure 5 shows an under-expanded jet scheme.

<Figure 5 is here>

The under-expanded jet scheme (Fig. 5) and the system of equations for an under-expanded jet with losses (Table 1) are described as follows. Parameters with subscript 1 correspond to high-pressure storage where the assumption of zero flow velocity is applied. The flow parameters at the entrance to the leak channel (nozzle) are referred to by subscript 2, and at the nozzle exit by subscript 3. It is assumed that the flow is choked at the nozzle/channel's exit (state 3) and therefore exit velocity is equal to local speed of sound. The notional nozzle exit, where parameters correspond to a fully expanded jet (pressure is equal to ambient), is referred to by subscript 4. It is assumed that at state 4 the flow velocity is uniform and locally sonic. It is also assumed that there is no air entrainment to the jet through the notional nozzle boundary (between states 3 and 4).

Minor losses are represented by an abrupt reduction or increase in the channel cross-section area, presence of valves, etc. They are described through the minor losses coefficient K, which is at the entrance to a pipe from a reservoir for the square-edged opening is equal to K=0.5. Frictional losses are considered to be due to friction at the walls through equation $F=fL/D$, where f is the friction factor, L is the channel/nozzle length of diameter D. The system of 12 equations describing this process is given in Table 1.

<Table 1 is here>

The system of equations in Table 1 can be reduced to the following two equations with two unknown parameters, i.e. u_3 and T_3,

$$\frac{u_3}{b}\left(1-\frac{\sqrt{\gamma R_{H2} T_3}}{u_3}\right)\cdot\left[\sqrt{\frac{R_{H2}T_3}{\gamma}}+\left(\frac{K+F}{4}\right)\cdot\sqrt{\frac{2}{K}\left(C_P T_1 - C_P T_3 - \frac{u_3^2}{2}\left(\frac{F}{4}+1\right)\right)}+u_3\left(\frac{F}{4}+1\right)\right]-P_1=0\,, \quad (4)$$

$$\frac{u_3}{b}\left(1-\frac{\sqrt{\gamma R_{H2} T_3}}{u_3}\right)\left[\frac{R_{H2}\left(T_1-\left(T_1-T_3-\frac{u_3^2}{2c_P}\left(\frac{F}{4}+1\right)\right)\frac{K+1}{K}\right)}{\sqrt{\frac{2}{K}\left(c_P T_1 - c_P T_3 - \frac{u_3^2}{2}\left(\frac{F}{4}+1\right)\right)}-u_3+\sqrt{\gamma R_{H2}T_3}}+\right.$$

$$\left.+\left(\frac{K}{4}+1\right)\sqrt{\frac{2}{K}\left(c_P T_1 - c_P T_3 - \frac{u_3^2}{2}\left(\frac{F}{4}+1\right)\right)}\right]-P_1=0\,. \quad (5)$$

After u_3 and T_3 are found by solving Eqs. (4) and (5), the rest of under-expanded jet parameters can be easily calculated.

Both the under-expanded jet theory without losses [29] and the under-expanded jet theory with losses [42] are applied to calculate parameters of under-expanded hydrogen jet exiting from a narrow channel of 0.75 mm diameter and 15 mm length at storage pressures up to 40 MPa (Table 2). The ambient temperature is assumed 287.65 K. The correlation by Nikuradse for friction factor $1/\sqrt{f} = 0.869 \cdot \ln\left(\mathrm{Re}\sqrt{f}\right) - 0.8$ is applied. The Reynolds number in this formula is taken as an average of values at states 2 and 3. The results of predictions by the under-expanded jet theories are compared against simulations by a RNG LES model. The solver used explicit linearization of the governing equations with explicit method for solution of the linear equations set. The second order upwind scheme with AUSM flux splitting is applied for flow discretisation. The four step Runge-Kutta algorithm is employed for advancement of simulations in time. The Courant-Friedrichs-Lewy number is *CFL*=0.5 to ensure stability. Total number of CVs is of the order of 100k.

<Table 2 is here>

Predictions by the under-expanded jet theory with losses are found to closely reproduce the numerical simulations whereas the theory without losses essentially over predicts the mass flow rate. The LES results somewhat above the predictions by the theory with losses at high pressures. It is thought due to use of the ideal gas law in the simulations.

Under-expanded jet theories ignoring losses can be a subject of large error in calculation of jet parameters, especially when considering narrow cracks. They can essentially over predict the mass flow rate and the flame length.

4. THE LIMITATION OF FROUDE-BASED CORRELATIONS

Nearly all correlations for jet flame length are based on the Froude number in one or another form, including recently published correlations by Schefer et al. [35],[36] that incorporate data on under-expanded jet fires. To include under-expanded jet fires into the dimensionless correlation [35] Schefer et al. substituted actual nozzle diameter by effective (notional) nozzle diameter. In their following study [36] the effective diameter was taken as mentioned above in the form $D_{eff}=D(\rho_N U_N/\rho_{eff} U_{eff})^{0.5}$, and is accepted here to build a correlation presented in Fig. 6.

Unfortunately, only limited number of own experiments with under-expanded jet fires was included to validate the *Fr*-based correlations in papers [35],[36]. In this section we investigate the predictive capability of *Fr*-based correlations for flame length of highly under-expanded hydrogen jets fires by inclusion into the analysis a wider range of experimental data reported by different authors.

Parameters at the notional nozzle exit are used to build the correlation in Fig. 6 for the flame length, following the statement by authors [36]. These parameters were calculated for the correlation shown in Fig. 6 using the under-expanded jet theory by Schefer et al. [36]. The dimensionless flame length and Froude number coordinates in the correlation (Fig. 6) are the same as in Schefer et al. [36]

$$L^* = \frac{L_F f_S}{d_{eff}(\rho_{eff}/\rho_S)^{1/2}} \quad \text{and} \quad Fr_f = \frac{U_{eff} f_S^{3/2}}{(\rho_{eff}/\rho_S)^{1/4}[(\Delta T_f/T_S) g d_{eff}]^{1/2}} \quad , \tag{6}$$

where f_S is introduced to unify the correlation for different fuels similar to other studies. The following constants are accepted: f_S=0.0281 (29.5% by volume of hydrogen in air), ρ_S=1.2 kg/m^3, ΔT_f=2092 K, T_S=298 K, g=9.82 m/s^2.

<Figure 6 is here>

Figure 6 demonstrates that flame length data are unacceptably scattered in the momentum-dominated area of the correlation with large Froude numbers, which are typical for leaks from high pressure hydrogen equipment. It is clear that the simplification of flame length correlations to functional dependence on Froude number only, i.e. with ignoring the theoretically predicted and experimentally observed dependence on Reynolds and Mach numbers, does not make it acceptable when under-expanded jets are included.

5. SIMILITUDE ANALYSIS AND FORMER DIMENSIONAL CORRELATION

Kalghatgi [27] proved experimentally that the flame length of a hydrogen jet into still air is affected by both the nozzle diameter and the mass flow rate. This observation was reconfirmed by Schefer et al. [35] and implies that jet flame length correlations, which take into account dependence on the diameter only, e.g. Hawthorne et al. [2], or the mass flow rate only, e.g. Mogi et al. [28], are lacking physical reasoning underpinned by the experimental data. In this section the dimensional correlation, which includes the dependence of flame length on both nozzle diameter and mass flow rate, is discussed [43].

Let us apply the similitude analysis to correlate the flame length, L_F, with the actual nozzle diameter, D, the density of hydrogen in the actual nozzle exit, ρ_N, the density of surrounding air, ρ_S, the viscosity, μ_N, and the velocity in the actual nozzle exit, U_N. The Buckingham Π theorem states that for a problem with 6 physical quantities and 3 dimensions, the quantities can be arranged into (6-3)=3 independent dimensionless Π parameters. These three Π parameters can be easily derived by the repeating variables or other methods as e.g. $\Pi_1=D/L_F$, $\Pi_2 = \rho_N / \rho_S$, and $\Pi_3 = \rho_N D U_N / \mu_N$. To develop the flame length correlation with both the diameter, D, and the mass flow rate, $\dot{m}$, it is convenient to modify some of the Π parameters to form a new dimensionless group $\Pi_1 \times \Pi_3^{1/2} = (\dot{m} \cdot D)^{1/2} / [L_F \cdot (\pi \mu_N / 4)^{1/2}]$. From this dimensionless group the following functional dependence can be suggested for the validation against experimental data

$$L_F = f\left[(\dot{m} \cdot D)^{1/2} \sqrt{\frac{4}{\pi \mu_N}} \right], \tag{7}$$

where the parameter in brackets has the length dimension similar to the left hand side of Eq. (7), L_F.

The experimental data by Kalghatgi [27] shown in Fig. 4 in the original coordinates $L_F - \dot{m}$ are quite scattered. Contrary, Fig. 7 shows a convergence of the Kalghatgi's experimental data onto the same curve (black circles for subsonic jet fires, and black diamonds for sonic (choked) flames) in the obtained by the similitude analysis coordinates L_F–$(\dot{m} \cdot D)^{1/2}$, as well as the same data in the original coordinates $L_F - \dot{m}$ (hollow circles, abscissa axis is on the top).

<Figure 7 is here>

The use of new similarity group $(\dot{m} \cdot D)^{1/2}$ has essentially improved the convergence of the flame length data by Kalghatgi [27] for both subsonic and sonic jets (see Fig. 7). Following this encouraging result, let us expand the analysis and include into the dimensional correlation along with experimental data by Kalghatgi [27] data obtained by other researchers: Mogi et al. [28], Schefer et al. [35],[36], and experimental data by researchers from INERIS (France) [39],[40],[41]. Figure 8 consolidates in coordinates L_F–$(\dot{m} \cdot d)^{1/2}$ 95 experimental data points on hydrogen jet flame length in a wide range of pressures up to 90 MPa and nozzle diameters 0.4-10.1 mm [43].

<Figure 8 is here>

The experimental data obtained by different research groups are collapsed onto the same curve, with the best fit line in Fig. 8 being described by the following dimensional equation (L_F is in meters)

$$L_F = 76 \cdot (\dot{m} \cdot D)^{0.347}, \tag{8}$$

where D is the actual nozzle diameter, m; and $\dot{m}$ is the mass flow rate, kg/s. This equation requires knowledge of the actual leak diameter and the mass flow rate only. They can be calculated using a validated under-expanded jet theory. It is worth noting that this methodology does not require substituting the actual nozzle diameter by the notional nozzle diameter. This excludes additional uncertainty in determination of parameters at notional nozzle exit related to particular assumptions of an under-expanded theory applied. This correlation has been validated against subsonic, sonic, and supersonic hydrogen jet flames.

The upper limiting curve for the experimental flame lengths in Fig. 8 (conservative estimate), is represented by equation $L_F = 116 \cdot (\dot{m} \cdot D)^{0.347}$ that yields 50% longer flame length compared to the best fit line described by Eq. (8).

Correlation (8) gives practically a linear dependence of the flame length on the nozzle diameter, $L_F \sim D$. In contrast, the correlation shows a weaker dependence of the flame length on the density and the velocity in the nozzle, $L_F \sim (\rho_N \cdot U_N)^{1/3}$. There could be a contribution to data scattering in Fig. 8 of hydraulic pressure losses which are expected to be different for each particular experimental set-up.

Predictive capability of the dimensional correlation in Fig. 8 is quite good for high debit jet fires (20%), and yet it is about 50% for smaller flames, where the characteristic peak in the dependence L_F/D=f(Re) for small diameters (see Figs. 2 and 3) is one of possible reasons of the larger scattering in the experimental data. While the correlation is a convenient and reliable tool for hydrogen safety engineering at large mass flow rate leaks it is not shedding a light on the underlying the correlation physics, and its low predictive capability at smaller leaks.

It should be emphasized that the correlation must be applied to small diameter leaks with caution. Indeed, experiments published elsewhere [28],[44] showed that a sustained hydrogen flame is possible only when a leak size is above the limit for a particular storage pressure. As have been mentioned above, no stable flames were observed for nozzle diameters 0.1-0.2 mm by Mogi et al. [28] at pressures up to 40 MPa. In line with this, a stable jet flame can exist at a pressure of 35 MPa if only the orifice diameter is above 0.3 mm [44].

6. NOVEL DIMENSIONLESS FLAME LENGTH CORRELATION

Practically all former flame length correlations are *Fr*-based and built on experimental data for subsonic buoyant jet/plume fires with a limited number of momentum-controlled jet fires at moderate pressures. Figure 6 shows that the *Fr*-based “correlation” is lacking physical commonality when a large number of experimental data on under-expanded jet fires (all in the momentum-dominated regime) are included.

Theoretical and experimental results indicate that the flame length has to be a function of not only the Froude number (Fr) but also the Reynolds (Re) number and the Mach (M) number. The analysis of previous research allows to conclude that it is impossible to build a universal correlation applicable to both expanded and under-expanded jet fires based on only one of these three similarity groups, and a new in principle approach is needed to correlate the experimental data properly.

Dimensional correlations like one in the previous section (see Fig. 8) are convenient engineering tools yet do not differentiate between different jet fire regimes. This section aims to advance our understanding of hydrogen jet flame behaviour, and develop a dimensionless correlation for non-premixed flames that will distinguish between traditional buoyancy-controlled and momentum-dominated jet flames, as well as between expanded and under-expanded jet fires.

The dimensional correlation (8) can be approximated as $L_F \propto (\dot{m} \cdot D)^{1/3}$. The mass flow rate is by definition $\dot{m} \propto D^2$. Thus, a conclusion can be drawn after substitution of $\dot{m} \propto D^2$ into relationship for L_F that the dimensional flame length, L_F/D, does not depend explicitly on the diameter, D. This is a basic hypothesis behind the development of a novel dimensionless correlation for the jet flame length, which is supported by the experimental data analysis. The only dependence of the dimensionless flame length, L_F/D, is then on the “residual” parameters in the mass flow rate, i.e. density ρ_N and velocity U_N at the nozzle exit, which are assumed uniform for the simplicity. The density and velocity can be normalized as ρ_N/ρ_S and U_N/C_N respectively, where C_N is the speed of sound at conditions of gas in the nozzle and ρ_S is the density of the surrounding air. In assumption of the kinetic energy flux in the nozzle exit to be a conserved scalar of the process a relation between the density and the velocity in the dimensional group can be suggested as $(\rho_N/\rho_S)(U_N/C_N)^3$.

Figure 9 presents a novel dimensionless hydrogen flame length correlation. In this correlation the experimental data on flame length are normalized by the actual (not notional) nozzle diameter, and are correlated with the product of the dimensionless density ratio ρ_N/ρ_S and the Mach number (ratio of the flow velocity to the speed of sound at the actual nozzle exit) to the power of three $M^3=(U_N/C_N)^3$.

<Figure 9 is here>

One of the advantages of this correlation is absence of parameters at the notional nozzle exit. The parameters needed to predict the flame length are those at the actual nozzle exit only: diameter, hydrogen density and flow velocity, the speed of sound at pressure and temperature at the nozzle exit. The use of the correlation requires application of an under-expanded jet theory. There is lesser uncertainty in calculation of flow parameters in the actual nozzle exit compared to uncertainties at the notional nozzle. Indeed, it is well known that there is a strong non-uniformity of velocity immediately downstream of the Mach disk that deviates from the common for all under-expanded jet theories assumption of uniform velocity at the notional nozzle exit. By this fact, the methodology excludes from consideration the questionable issue of use of flow parameters at the notional nozzle exit.

The hydrogen flow parameters at the nozzle exit for experiments presented in Fig. 9 are taken either directly from the experiments or calculated by the under-expanded jet theory [29]. The details of experiments used to underpin the dimensionless correlation are given in [45]. The novel correlation covers the whole spectrum of hydrogen reacting leaks, including laminar and turbulent flames, buoyancy- and momentum-controlled fires, expanded (subsonic and sonic) and under-expanded (sonic and supersonic) jet fires.

The dimensionless group derived for correlating the dimensionless flame length can be rewritten in terms of Re and Fr numbers as follows

$$\frac{\rho_N}{\rho_S}\cdot\left(\frac{U_N}{C_N}\right)^3=\frac{g\cdot\mu_N}{\rho_S\cdot C_N^3}\cdot\mathrm{Re}\cdot Fr\,, \tag{9}$$

where the viscosity was calculated as $\mu_N=\mu_{293}\cdot\left((293+K_{Suth})/(T_N+K_{Suth})\right)\cdot\left(T_N/293\right)^{3/2}$ (Sutherland constant for hydrogen was taken as K_{Suth} = 72 K and the dynamic viscosity as μ_{293} =

8.76×10^{-6} Pa·s), and *Re* and *Fr* are determined by parameters of hydrogen flow in the actual nozzle exit as $\mathrm{Re} = (\rho_N \cdot U_N \cdot D)/\mu_N$ and $Fr = U_N^2/(g \cdot D)$.

The form of the dimensionless group in the left hand side of Eq. (9) suggests that for subsonic flows, when M<1, the dimensionless flame length depends on the nozzle Mach number only, as the density ratio ρ_N/ρ_S is practically a constant for expanded jets (in assumption of constant temperature in the nozzle). For choked flows (M=1) the dimensionless flame length depends only on the hydrogen density in the nozzle exit ρ_N. The density increases with the increase of storage pressure and the decrease of temperature.

The form of the right hand side of Eq. (9) indicates that at a constant temperature of hydrogen in the nozzle exit (that provides the constancy of the speed of sound C_N) the dimensionless flame length depends on both *Re* and *Fr* numbers. This is contrary to the former correlations built on *Fr* number only.

There are three distinct parts in the novel dimensionless correlation in Fig. 9 (from the left to the right): traditional buoyancy-controlled, traditional momentum-dominated "plateau" (expanded jets), and new momentum-dominated under-expanded jet fire "slope" part. These three parts can be approximated by the following equations (conservative curves) respectively

$$\begin{aligned} L_F/D &= 1403 \cdot \left[(\rho_N/\rho_S)\cdot(U_N/C_N)^3\right]^{0.196}, \quad for \quad (\rho_N/\rho_S)\cdot(U_N/C_N)^3 < 0.0001;\\ L_F/D &= 230, \quad for \quad 0.0001 < (\rho_N/\rho_S)\cdot(U_N/C_N)^3 < 0.07;\\ L_F/D &= 805 \cdot \left[(\rho_N/\rho_S)\cdot(U_N/C_N)^3\right]^{0.47}, \quad for \quad (\rho_N/\rho_S)\cdot(U_N/C_N)^3 > 0.07. \end{aligned} \tag{10}$$

There is a saturation of L_F/D for expanded jet fires as the flow velocity in the actual nozzle exit is approaching the speed of sound. The value of this saturation limit L_F/D =230 reproduces results of a number of previous studies with expanded jets, though in the new coordinates. However, there is no saturation of the dimensionless flame length for choked under-expanded jet flames. Reported in recent under-expanded jet fire experiments [39] values are significantly higher compared to the limit L_F/D =230 - up to and above L_F/D=3000.

There are some experimental points of Schefer et al. [35] in Fig. 9 that are below the rest of the data. It is thought due to losses in this particular experimental set-up, which is not described in detail sufficient to allow the application of the under-expanded jet theory with losses. Indeed, the losses would decrease the density in the nozzle exit and those points would be shifted to the left along the abscissa axis closer to the correlation. The experimental set-up that was used in the next study of Schefer et al. [36] had obviously lesser flow losses and pressure given was measured closer to the nozzle.

The shape of data in Fig. 9 has a physical meaning based on the knowledge of jet flame behavior. For example, the dimensionless flame length, L_F/D, increases for laminar and transitional flames (usually identified as "buoyancy-controlled" regime, low *Re*), then it is practically constant for transitional and fully developed turbulent expanded flames ("momentum-dominated" regime, moderate *Re*), and it increases again for under-expanded jets (higher *Re*). The last is due to the fact that the dimensionless flame length is defined through the actual nozzle exit diameter, which is a constant, while in reality the under-expanded jet expands to atmospheric pressure at the notional nozzle exit which increases with increase of density in the nozzle.

Figure 10 demonstrates changes of dimensionless numbers *Re, Fr, M* (for the experiments used for the development of the dimensionless correlation) as a function of the similarity group $(\rho_N/\rho_S)(U_N/C_N)^3$. The analysis of *Re, Fr, M* functional dependence on the similarity group shows that for under-expanded jets the dimensionless flame length growth depends practically on *Re* only. Indeed, the nozzle flow for under-expanded jets is choked, i.e. local M=1, and the nozzle *Fr* number is practically constant also (the scattering of *Fr* is due to difference in nozzle diameters of about one order of magnitude).

<Figure 10 is here>

There are five dashed thick lines in Fig. 10. Line Re=2000 indicates the start of transition from laminar to turbulent nozzle flow. Close to (or immediately above) this line there are experimental points with laminar jet flames and jet flames in the transitional regime. Horizontal line M=1 indicates a choked flow limit. Subsonic expanded jets have M<1 and sonic and supersonic (relevant to flow in the notional nozzle) under-expanded jets have M=1 in the nozzle exit. There is some scattering of data around M=1 due to experimental data and data processing errors. Horizontal line $Fr=10^6$ is an approximate division between buoyancy-controlled ($Fr<10^6$) and momentum-dominated ($Fr>10^6$) jets established previously for expanded jets.

Vertical line at a value of the similarity group $(\rho_N/\rho_S)(U_N/C_N)^3$=0.0001 conditionally separates buoyant jet fires (to the left from the line) and momentum jet fires (to the right from the line). Finally, vertical line denoted M=1 divides subsonic (to the left) and sonic or chocked (to the right) jets in the nozzle exit.

In log-log coordinates in Fig. 10 *Fr* number increases linearly with the similarity group $(\rho_N/\rho_S)(U_N/C_N)^3$ for expanded jet fires. There is practically no change of *Fr* for under-expanded jets in this system of coordinates (scattering is mainly due to difference in nozzle sizes). There is a slight growth of *Re* with the similarity group for buoyant jets, moderate increase in traditional momentum-dominated area, and comparatively steep growth of *Re* number in the area of under-expanded jet fires that are all momentum-dominated.

The novel dimensionless correlation is validated in the range of hydrogen storage pressures from nearly atmospheric up to 90 MPa, temperatures down to 80 K, and nozzle diameters from 0.4 to 51.7 mm. The predictive capability of this dimensionless correlation exceeds that of *Fr*-based only correlations, and it clearly distinguishes three regimes of jet fires, i.e. buoyancy-controlled, momentum-dominated (expanded), momentum-dominated (under-expanded).

7. FLAME TIP LOCATION AND EQUIVALENT UNIGNITED JET CONCENTRATION

This is a wide spread and unfortunately incorrect point of view that had been published for the first time in 1957 [4] and repeated later at least in 1975-1976 [5],[6] that the calculated flame length may be obtained by substitution the concentration corresponding to the stoichiometric mixture (29.5% by volume of hydrogen in air) in equation of axial concentration decay for a non-reacting jet.

The analysis of experimental data that has been carried out in this study has demonstrated that the longest, and thus hazardous, flames as expected are for under-expanded jets. This is important to underline that all experimental data on under-expanded jet fires are in the momentum-dominated regime due to high velocity of chocked flows and comparatively small diameters of piping for equipment working at pressures up to 100 MPa. Recently the similarity law for axial concentration decay in round unignited expanded momentum-dominated jets, suggested by Chen and Rodi [22], has been extended and thoroughly validated for under-expanded hydrogen jets [7]

$$\frac{C_{ax}}{C_N} = 5.4\sqrt{\frac{\rho_N}{\rho_S}}\frac{D}{x}, \tag{11}$$

where C_{ax} is the mass fraction of gas at axial distance x from the nozzle, C_N is a mass fraction of gas in the nozzle (C_N=1 for pure gas release), x is the axial distance from the nozzle, and density at the nozzle exit ρ_N is the only unknown parameter.

The application of the similarity law (11) to axial concentration decay in expanded jet is straight forward with the use of a constant hydrogen density in a nozzle, e.g. ρ_N=0.0838 kg/m^3 at normal temperature and pressure (NTP). However, for under-expanded jets the knowledge of density in the nozzle, ρ_N, as a function of storage pressure and losses in a leak pathway is necessary. The density in the nozzle can be calculated using the under-expanded jet theory [29] for flows without losses or the described above theory for flows when losses cannot be neglected.

Figure 11 presents a correlation between location of hydrogen jet flame tip (flame length) and location of hydrogen concentration in unignited jet originating from the same leak source. Points in Fig. 11 represent the dimensionless experimental flame length, L_F/D. The diagonal lines in Fig. 11 correspond to the dimensionless distance x/D to location of particular axial hydrogen concentration, C_{ax}, as a function of the density in the nozzle, ρ_N, (recalculated to the storage pressure, p in atmospheres, in Fig. 11) and calculated using the similarity law (11).

<Figure 11 is here>

The conclusion can be drawn from Fig. 11 that for momentum-controlled round jet fires the flame tip is located where the axial concentration of hydrogen in an unignited jet from the same leak source is in the range between 8% and 16% by volume, depending on experimental conditions. The best fit line of 70 experimental points for hydrogen flame length of momentum-dominated jet fires is close to 11% by volume of hydrogen in air in unignited jet. These concentrations are below the stoichiometric concentration of 29.5% by volume as was thought previously [4],[5],[6], and as a result distances to these concentrations from the nozzle are longer by 2.2 time (16%) to 4.7 times (8%) than distance to axial concentration 29.5% (stoichiometric hydrogen-air mixture). This obviously could have serious safety implications.

8. SEPARATION DISTANCES FROM A HYDROGEN LEAK

Different engineering tools to calculate hydrogen jet flame length are developed and described above. They include the dimensional and dimensionless correlations for the jet flame length, as well as the methodology to calculate hydrogen axial concentration decay to 11% by volume in a unignited jet to evaluate the flame tip location (flame length). However, the question about separation distances from a leak source based on comparative analysis of hazards from unignited jet and jet fire is not yet finalised.

British standard [46] recommends 115°C as the threshold for pain from an elevated air temperature for exposure longer than 5 minutes. This is in line with the previously published classification [47] of elevated temperature effects on occupants: below 70°C, no fatal issue in a closed space except uncomfortable situation; between 70°C and 150°C, the impact is dominated by difficulties to breath; above 150°C, skin burns occur in less than 5 minutes and this is a limiting temperature for escape. Time to incapacitation in minutes as a function of air temperature (^{o}C) can be estimated by the following equations recommended by DNV [47] and BSI [48] respectively

$$t_{incap} = 5.33 \cdot 10^{8} \cdot T_{air}^{-3.66}, \tag{12}$$

$$t_{incap} = 5 \cdot 10^{7} \cdot T_{air}^{-3.4}. \tag{13}$$

For temperature 115^{o}C Eq. (12) gives the incapacitation time 5 minutes of exposure, and Eq. (13) gives 15 minutes. Temperature 115^{o}C is assumed in this study as the acceptance criteria for pain limit in hot air when considering an escape from an elevated temperature gas flow generated by a hydrogen jet fire. More details on physiological response of humans to air at elevated temperature are as follows [47],[49]: 127^{o}C - difficult breathing; 149^{o}C - mouth breathing difficult, temperature limit for escape; 160^{o}C - rapid, unbearable pain with dry skin; 182^{o}C - irreversible injuries in 30 seconds; 203^{o}C - respiratory systems tolerance time less than four minutes with wet skin; 309^{o}C - third degree burns for a 20 seconds exposure, causes burns to larynx after a few minutes, escape improbable.

Harm criteria for people can be expressed in terms of injury or death [50]. It is possible to use a "no harm" criterion which limits the level of acceptable consequences to a low enough level that no injury would occur. Temperature 70^{o}C is taken as "no harm" criterion in this study. Exposures to flames, hot air or radiant heat fluxes can result in first, second, or third degree burns. The resulting level of harm is dependent upon several factors: the amount and location of exposed skin, the person's age, the exposure time, the speed and type of medical treatment, etc.

Figure 12 shows measured axial temperature of hydrogen flame [38],[50],[51] as a function of distance from the nozzle, x, normalised by the flame length, L_F. Three accepted here criteria are presented by horizontal lines: 70^{o}C - "no harm" limit; 115^{o}C - pain limit for 5 min exposure; 309^{o}C - third degree burns for a 20 s ("death" limit). Comparison between the axial temperature profile and named criteria provides the separation distances: x=3.5L_F for "no harm" separation (70^{o}C), x=3L_F for pain limit (115^{o}C, 5 min), x=2L_F for third degree burns (309^{o}C, 20 s).

<Figure 12 is here>

Let us compare for the same leak source three separation distances for momentum-controlled jet fire and a separation distance for momentum-dominated unignited release (distance to the lower flammability limit, LFL, of 4% by volume of hydrogen in air). It is demonstrated in this paper that the statistically averaged flame length is equal to the distance from the nozzle to an axial location where hydrogen concentration decays to 11% by volume in unignited jet (data are scattered from 8% to 16% by volume).

The similarity law (11) for concentration decay in a unignited momentum-controlled jets requires the use of hydrogen mass fraction and not volumetric fraction as mistakenly used by some researchers. The mass fraction (C_M) can be calculated by the volumetric (mole) fraction (C_V) by equation $1/C_M=1+(1/C_V -1)M_S/M_N$, where M_S and M_N are molecular mass of surrounding gas and nozzle gas respectively. For air composition 21% by volume of oxygen and 79% of nitrogen the mass fraction of hydrogen C_{ax}=0.002881 corresponds to 4% of hydrogen by volume in air, 0.008498 corresponds to 11% by volume (0.005994 – 8%, 0.013037 – 16%), and mass fraction of stoichiometric mixture is 0.0282 (29.5% by volume).

The ratio of distances from the nozzle to axial concentration 11% by volume (correct flame tip location obtained in this study) and to 29.5% by volume (incorrect location of the flame tip suggested in some studies) can be estimated by dividing two similarity laws (11) for these two concentrations by each other (in assumption that the similarity law is applicable up to concentrations as high as stoichiometric), i.e. $x_{11\%}/x_{29.5\%}=C_{ax(29.5\%)}/C_{ax(11\%)}$=0.0282/0.008498= 3.3. This increases calculated flame length by an order of magnitude compared to that based on the previous knowledge.

The ratio of distances to LFL of 4% by volume and to the averaged flame tip location of 11% by volume is (it has to be noted that flame length is not equal to separation distance from the flame source): $x_{4\%}/x_{11\%}$=0.008498/0.002881=2.95 (LFL distance to longest flame length ratio is

$x_{4\%}/x_{8\%}$=2.08, and LFL to shortest flame ratio is $x_{4\%}/x_{16\%}$=4.53). Thus, ratios of the separation distance to LFL (unignited jet) to three separation distances based on the choice of harm criteria from reacting hydrogen jet are (for average flame tip location at concentration in unignited jet of 11% by volume): $x_{4\%}/x_{T=70C}=x_{4\%}/(3.5 \cdot x_{11\%})$=2.95/3.5=0.84; $x_{4\%}/x_{T=115C}$= 2.95/3=0.98; $x_{4\%}/x_{T=309C}$ =2.95/2=1.48. However, in the conservative case of the flame tip location at the concentration of 8% by volume in unignited jet, these three ratios will change to the following values respectively: $x_{4\%}/x_{T=70C(8\%)}$=0.005994/0.002881/3.5=2.08/3.5=0.59; $x_{4\%}/x_{T=115C(8\%)}$=2.08/3=0.69; $x_{4\%}/x_{T=309C(8\%)}$ =2.08/2=1.04.

As a result an "unexpected" conclusion can be drawn from the performed analysis that in the conservative case of hydrogen safety engineering all three separation distance for reacting release (jet fire) are longer or equal to the separation distance based on the lower flammability limit (unignited release). In particular, the separation distance from a hydrogen leak source to a location with axial concentration equal to the lower flammability limit, e.g. to prevent ingress of flammable mixture into a ventilation system of building, is practically equal to the "death" separation distance for reacting release (exposure to 309^{o}C during 20 s). Two other separation distances for jet fires ("no harm" and "pain" limits) are longer than separation distance to LFL (unignited release).

The revealed "longest" location of the hydrogen jet flame tip at axial distances from the nozzle corresponding to 8% by volume of hydrogen in unignited jet is a physically sound result. Indeed, this value is within the error to the lower flammability limit for downward and spherically propagating premixed hydrogen-air flames of 8.5-9.5% by volume. Thus, any combustion beyond this distance (at smaller concentrations) is "detached" from the area of "continuous" vertical flame.

Radial separation distance from hydrogen jet fire requires an analysis of radiative heat transfer rather than flow temperature. This is not a subject of this study and relevant information can be found elsewhere [36].

9. CONCLUSIONS

- The Froude number only based correlations are not applicable to under-expanded jets due to their inability to replicate the strong dependence of the dimensionless flame length on Reynolds number for under-expanded jets.

- The application of the similarity group in the form of a product of the mass flow rate and the actual nozzle diameter provided essential reduction of experimental data scattering for both subsonic and sonic jet flames in the coordinates $L_F - \dot{m} \cdot D$ compared to the original coordinates of Kalghatgi (1984) $L_F - \dot{m}$. The dimensional correlation for hydrogen jet flame length $L_F = 76 \cdot (\dot{m} \cdot D)^{0.347}$ has been developed as a best fit line for 95 experimental data published by different research groups at pressures up to 90 MPa and nozzle diameters up to 10 mm. The conservative equation for the flame length is L_F=116$\cdot$($\dot{m}\cdot D$)$^{0.347}$ (50% longer flame compared to the best fit line equation).

- The under-expanded jet theory accounting to non-ideal behaviour of hydrogen at high pressures as well as friction and minor losses in the leak pathway is presented. It is demonstrated that losses could strongly affect the mass flow rate (hydrogen density in the nozzle exit) and has to be accounted for in carrying out hydrogen safety engineering when relevant.

- The novel dimensionless correlation for hydrogen jet flame length in still air in the coordinates L_F/D–$(\rho_N/\rho_S)\cdot(U_N/C_N)^3$ is developed and described in detail. The correlation is validated against experimental data on laminar diffusion and non-premixed turbulent flames, buoyancy- and momentum-dominated flows, expanded and under-expanded hydrogen jet flames in the widest known to authors range of pressures 0.1-90.0 MPa, temperatures 80-300 K, and leaks diameters 0.4-51.7 mm.

- Three regimes of jet fires are identified, changing from traditional buoyancy-controlled at low values of dimensionless group $(\rho_N/\rho_S)\cdot(U_N/C_N)^3$, to traditional momentum-dominated "plateau" at moderated values, and finally to momentum-controlled under-expanded jet fire regime at higher values of $(\rho_N/\rho_S)\cdot(U_N/C_N)^3$.

- The statement of Sunavala et al. (1957) "calculated flame length may be obtained by substitution the concentration corresponding to the stoichiometric mixture in equation of axial concentration decay for non-reacting jet" was applied for more than 50 years and was reconfirmed by Bilger and Beck in 1975 and by Bilger in 1976. It is proved that this statement is not valid for non-premixed turbulent jets in the momentum-dominated regime. The locus of average location of hydrogen jet flame tip in the range of pressures 0.2-90 MPa is matched by a line with an average axial concentration in unignited jet of 11% by volume of hydrogen in air (data are scattered in the range of axial hydrogen concentration in non-reacting jets from 8% to 16% by volume). Location of these axial concentrations is farther from the nozzle compared to location of stoichiometric concentration of 29.5% by volume to which the location of the flame tip was attributed before. This conclusion has serious safety implications, e.g. distance from a leak source to axial concentration 11% by volume is 3.3 times longer than distance to the axial concentration 29.5% by volume (2.2 times longer for 16% by volume, and 4.7 times longer in the conservative case of 8% by volume).

- Three separation distances for jet fire include: "no harm" distance to temperature 70^{o}C, which is about 3.5 times of the flame length; "pain limit" (115^{o}C, 5 min), which is 3 times of the flame length; and "death limit" (309^{o}C, 20 s), which is 2 times longer than the flame length. The three separation distances for a hydrogen jet fire from a leak source are shown to be longer than separation distance for unignited jet (based on the lower flammability limit of 4% by volume) from the same source.

- In the conservative case of the flame tip location at the location of concentration of 8% by volume in unignited jet, the ratios of a distance to the axial concentration 4% by volume (LFL) in non-reacting jet to the three separation distances for a jet fire are: $x_{4\%}/x_{T=70C(8\%)}$=0.59; $x_{4\%}/x_{T=115C(8\%)}$=0.69; $x_{4\%}/x_{T=309C(8\%)}$=1.04. Thus, all three separation distances for reacting jet are longer (within 4% error for "death" limit) compared to the separation distance for non-reacting jet from the same leak source.

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Table

Table 1 – The system of equations for the under-expanded jet with losses **Error! Reference source not found.**.

$P_2 - P_1 + \rho_2 u_2^2 (K/4+1) = 0$	$\rho_2 u_2 = \rho_3 u_3$
$c_P T_1 = c_P T_2 + (K+1)\cdot u_2^2/2$	$u_3 = \sqrt{\gamma R_{H2} T_3}/(1-b\rho_3)$
$\rho_2 = P_2/(bP_2 + R_{H2}T_2)$ or $P_2 = \rho_2 R_{H2} T_2/(1-b\rho_2)$	$u_4 = a_4 = \sqrt{\gamma R_{H2} T_4}$
$P_3 - P_2 + \rho_2 u_2^2 (F/4-1) + \rho_3 u_3^2 (F/4+1) = 0$	$\rho_4 = P_4/(R_{H2}T_4)$
$c_P T_2 + u_2^2/2 = c_P T_3 + (F/4+1)\cdot u_3^2/2$	$c_P T_3 + u_3^2/2 = c_P T_4 + u_4^2/2$
$\rho_3 = P_3/(bP_3 + R_{H2}T_3)$	$\rho_3 u_3 A_3 = \rho_4 u_4 A_4$

Note: P – pressure, T – temperature, u – velocity, a – speed of sound, ρ – density, c_P – specific heat at constant pressure, b - co-volume constant in the Abel-Noble equation, b=0.007691 m^3/kg, R_{H2} – gas constant for hydrogen, A – cross-section area.

Table 2 – Mass flow rates (g/s) through 15 mm length and 0.75 mm diameter channel at different pressure.

Method of calculation	**0.53 MPa**	**10.5 MPa**	**40 MPa**
Under-expanded theory without losses	1.44	2.80	9.56
Under-expanded theory with losses	1.05	2.08	7.76
Large Eddy Simulation	1.05	2.10	8.10

Figure captions

Fig. 1 – Progressive change from laminar diffusion flame to fully developed turbulent non-premixed flame **Error! Reference source not found.**.

Fig. 2 – The theoretical dependence of the flame length to diameter ratio, L_F/D, as a function of Reynolds number, *Re*, for different nozzle diameters, *D*. Dotted horizontal line indicates a turbulent flame length limit L_t **Error! Reference source not found.**.

Fig. 3 – The experimental flame length to diameter ratio, L_F/D, as a function of Reynolds number, *Re*, for different nozzle diameters, *D*, mm **Error! Reference source not found.**: 1 – 1.45; 2 – 1.9; 3 – 2.9; 4 – 4.0; 5 – 6.0; 6 – 10.75; 7 – 15.5; 8 – 21; 9 – 51.7.

Fig. 4 – The original experimental data by Kalghatgi **Error! Reference source not found.** on hydrogen jet flame length for subsonic and sonic jet fires for different nozzle diameters and different mass flow rates. Arrows indicate the transition from subsonic (to the left from the arrow) to sonic flow.

Fig. 5 – The under-expanded jet scheme.

Fig. 6 – The *Fr*-based flame length correlation in coordinates used by Schefer et al. **Error! Reference source not found.** with the extended range of experimental data on under-expanded jet fires.

Fig. 7 – The experimental data by Kalghatgi **Error! Reference source not found.**: scattered in the original coordinates L_F–m (hollow circles), and converged in the coordinates L_F–$(m{\cdot}D)^{1/2}$ (black circles - subsonic, diamonds - sonic jet fires).

Fig. 8 – The dimensional correlation for hydrogen jet flame length.

Fig. 9 – The dimensionless correlation for hydrogen jet flames (in formulas "*X*" denotes the similarity group $(\rho_N/\rho_S)(U_N/C_N)^3$).

Fig. 10 – Dimensionless numbers *Re, Fr, M* as a function of the new similarity group for experiments used to build the dimensionless correlation.

Fig. 11 – The correlation between the dimensionless flame length, L_F/D, and distance to a particular concentration in a non-reacting jet, x/D, from the same leak source for different storage pressures, *p*.

Fig. 12 – Measured axial temperature as a function of distance expressed in flame calibres, and three criteria for jet fire effects (lines).

Figure 1
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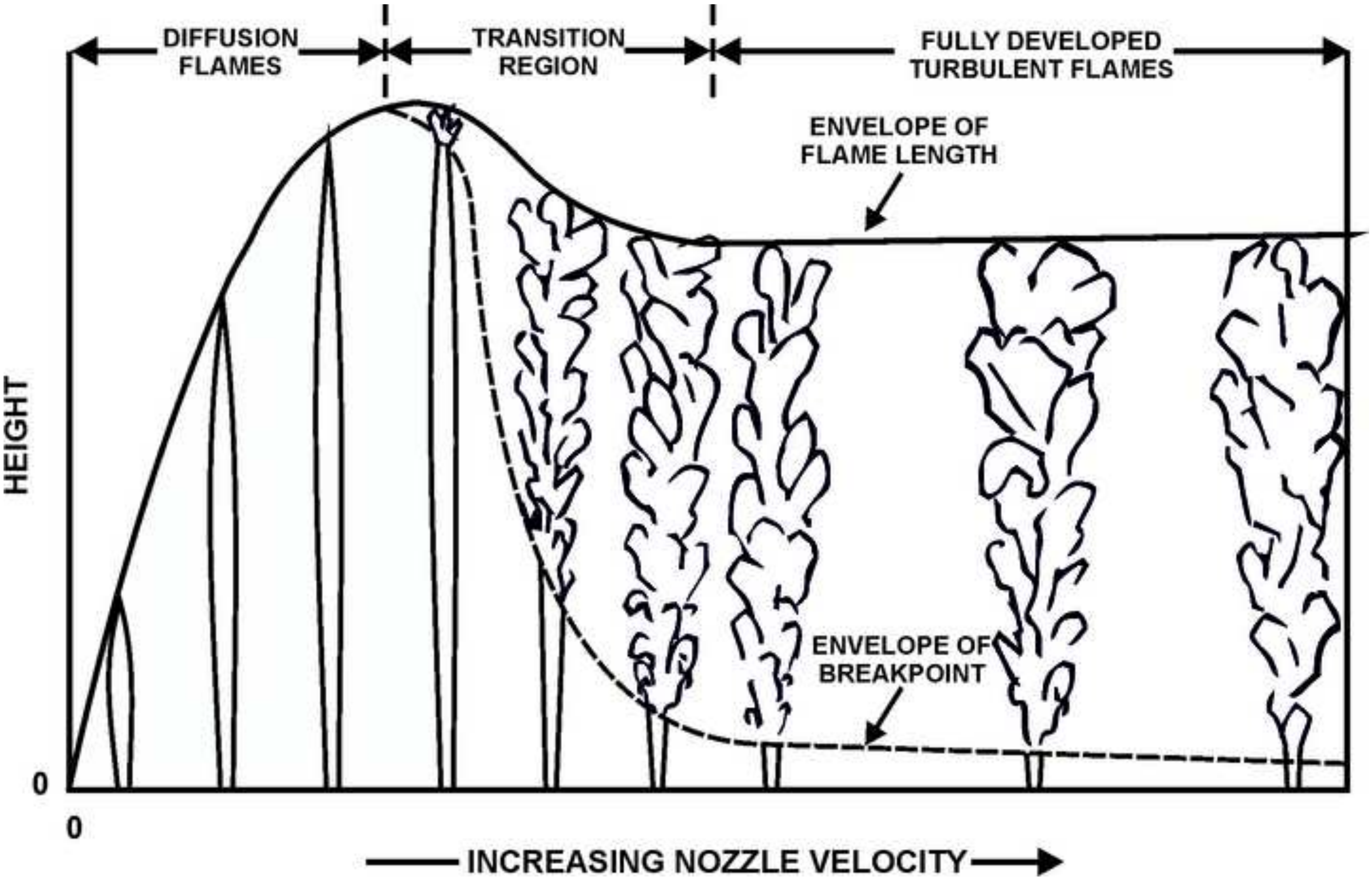

Figure 2
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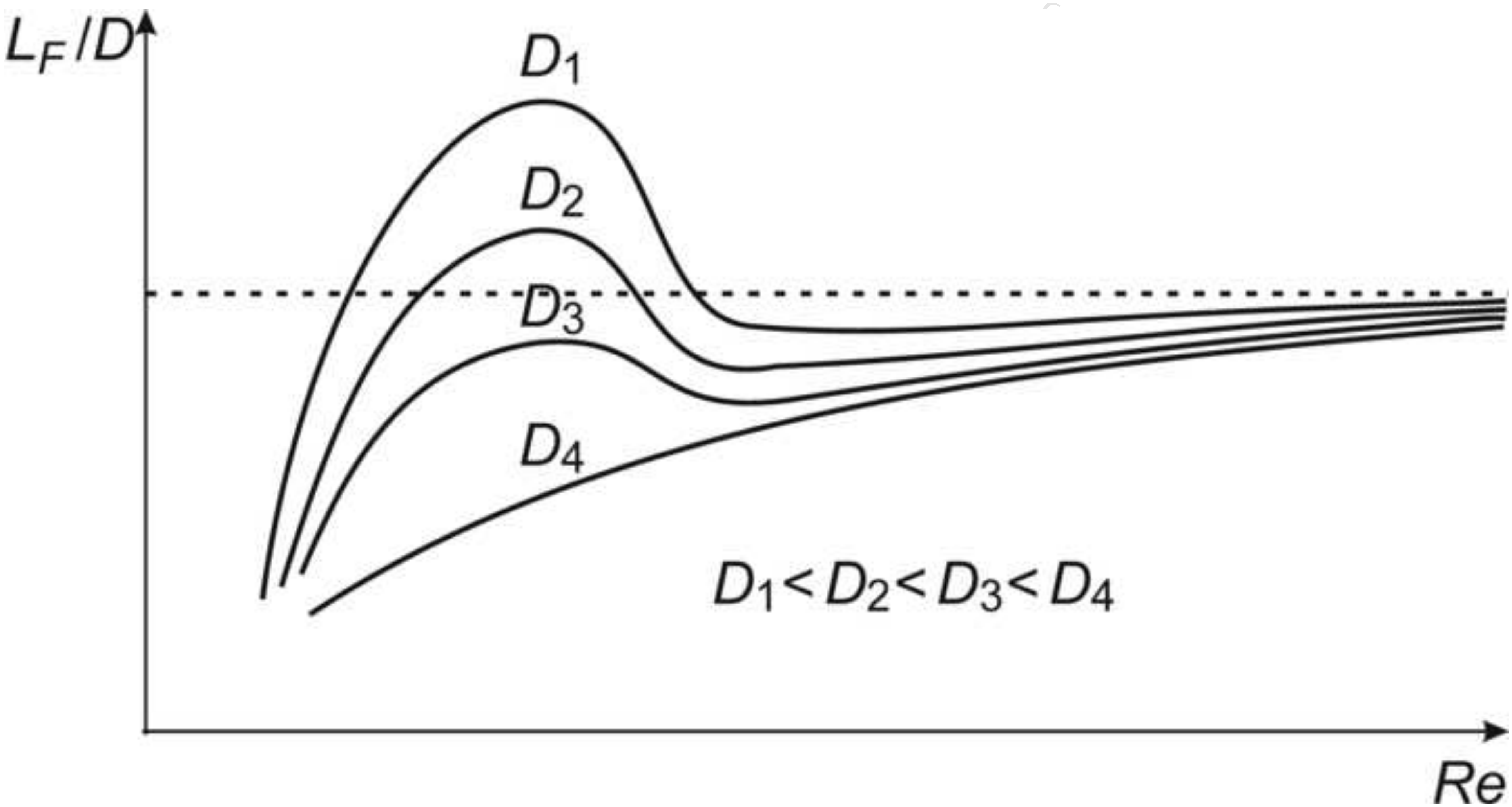

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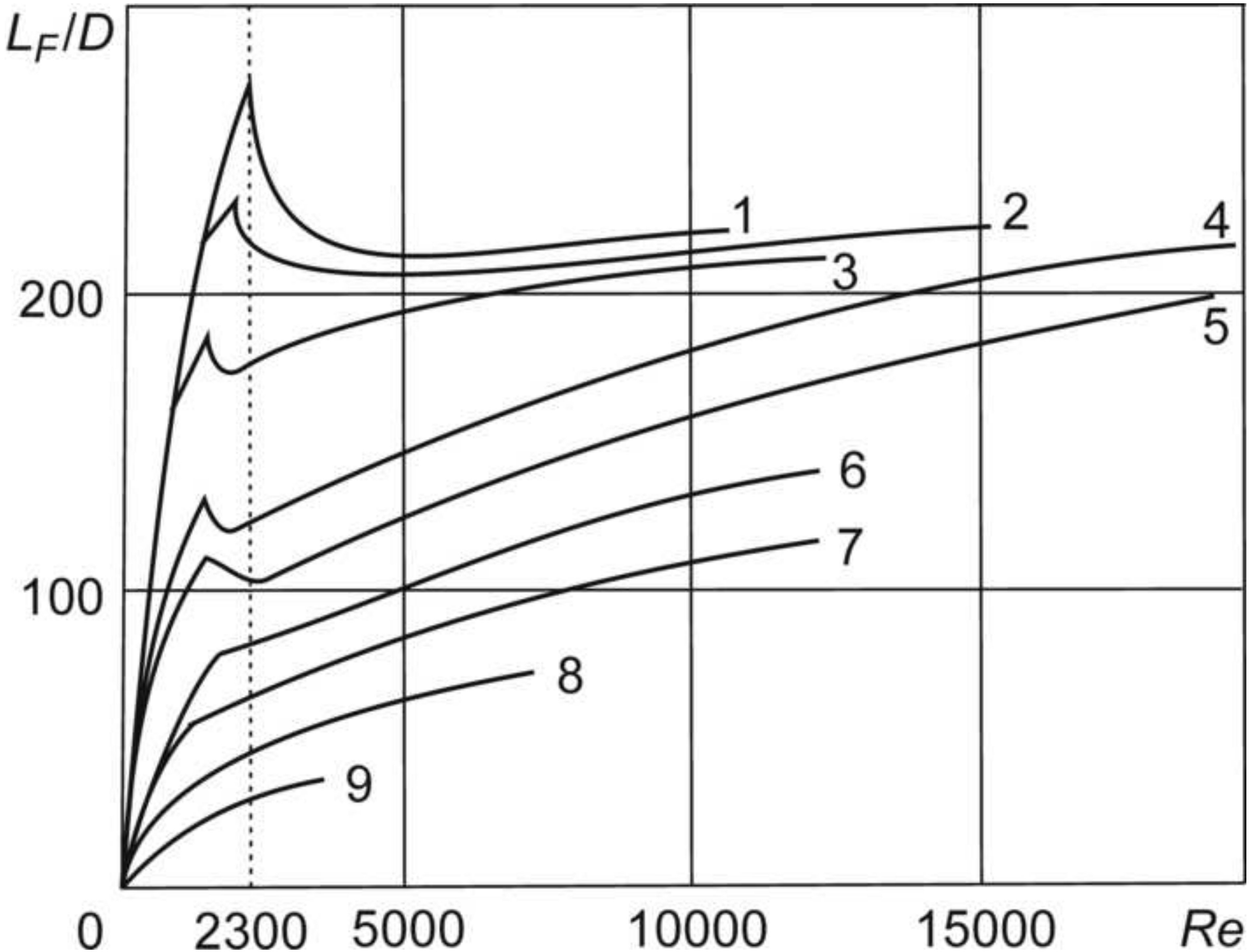

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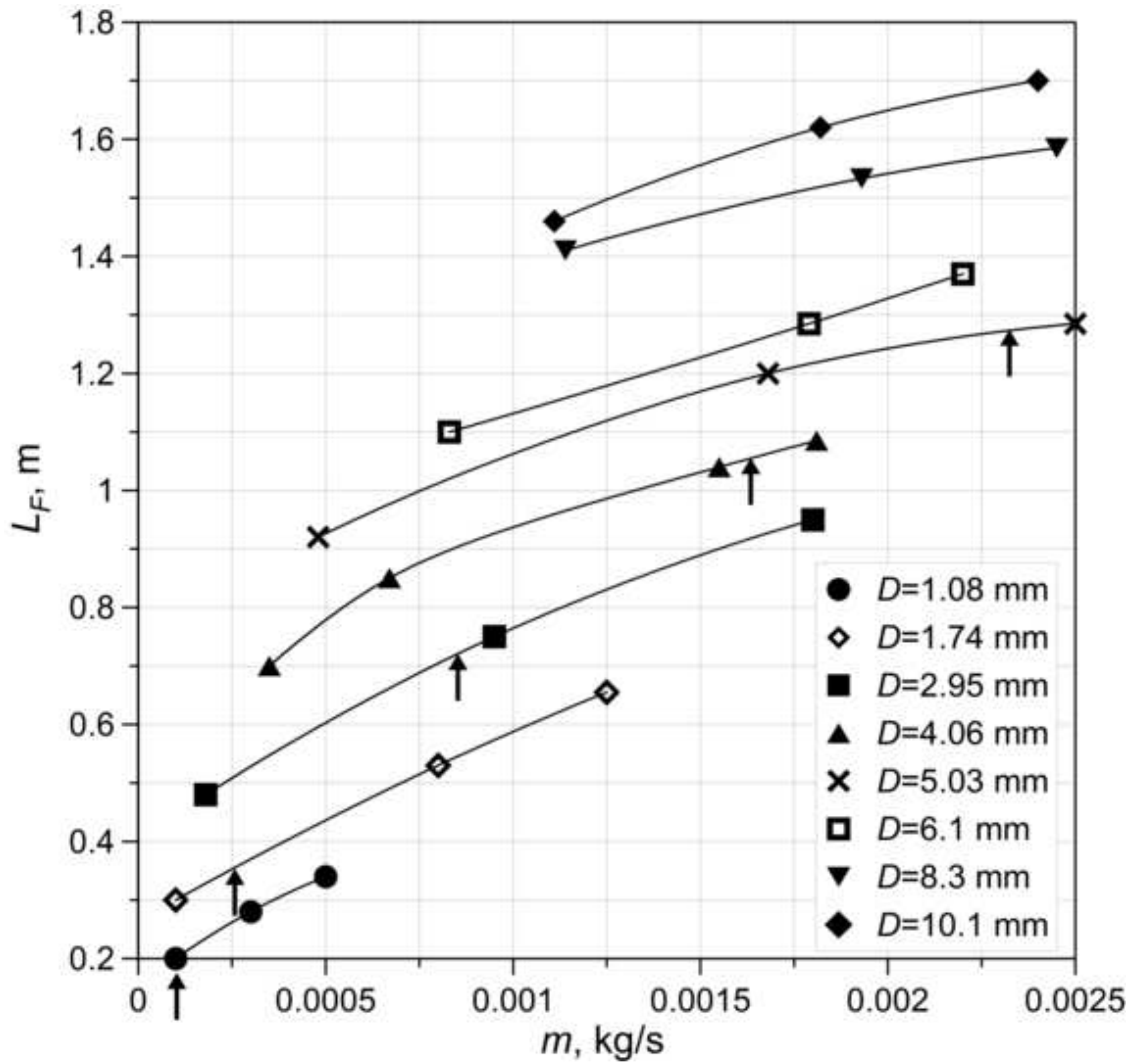

Figure 5

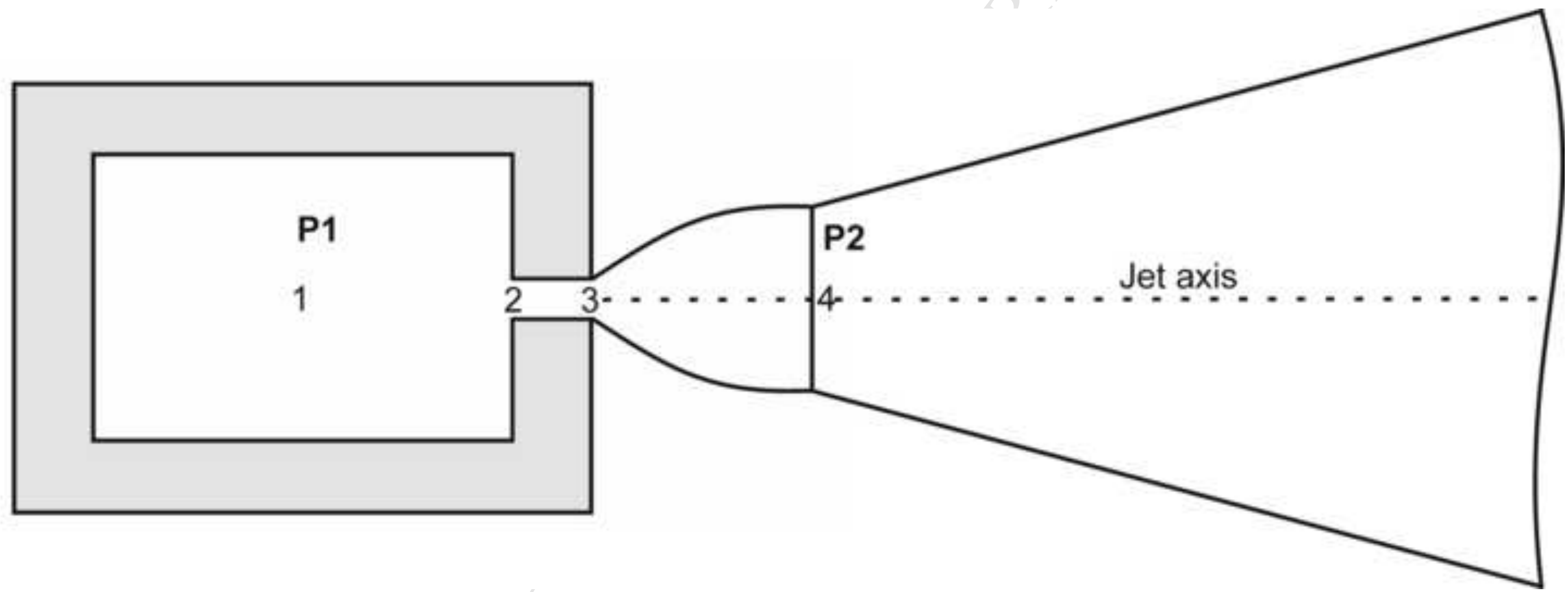

Figure 6

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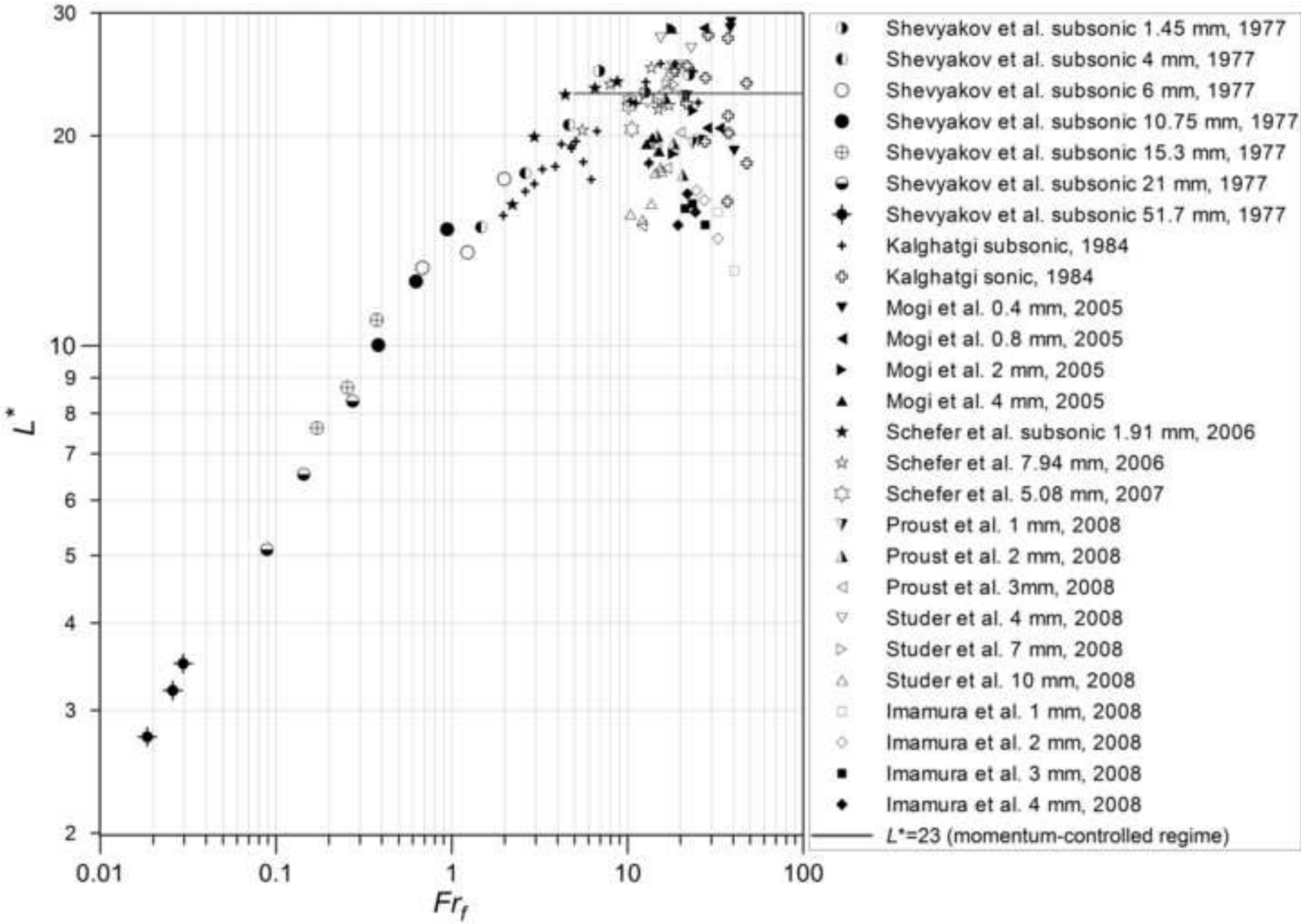
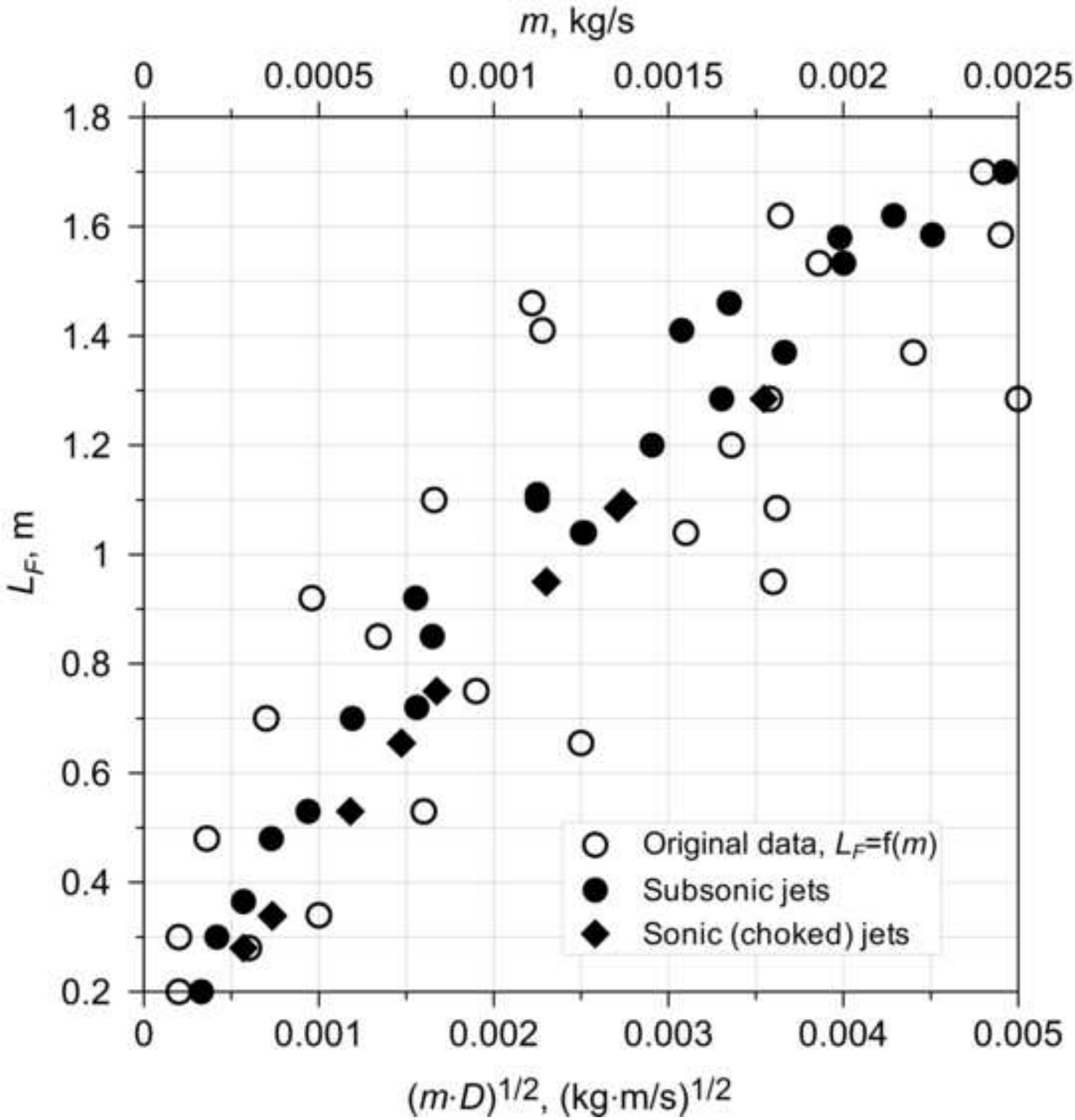


Figure 7



m, kg/s
0
0.0005
0.001
0.0015
0.002
0.0025
L_F, m
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.001
0.002
0.003
0.004
0.005
$(m \cdot D)^{1/2}$, $(kg \cdot m/s)^{1/2}$
Original data, L_F=f(m)
Subsonic jets
Sonic (choked) jets

Figure 8
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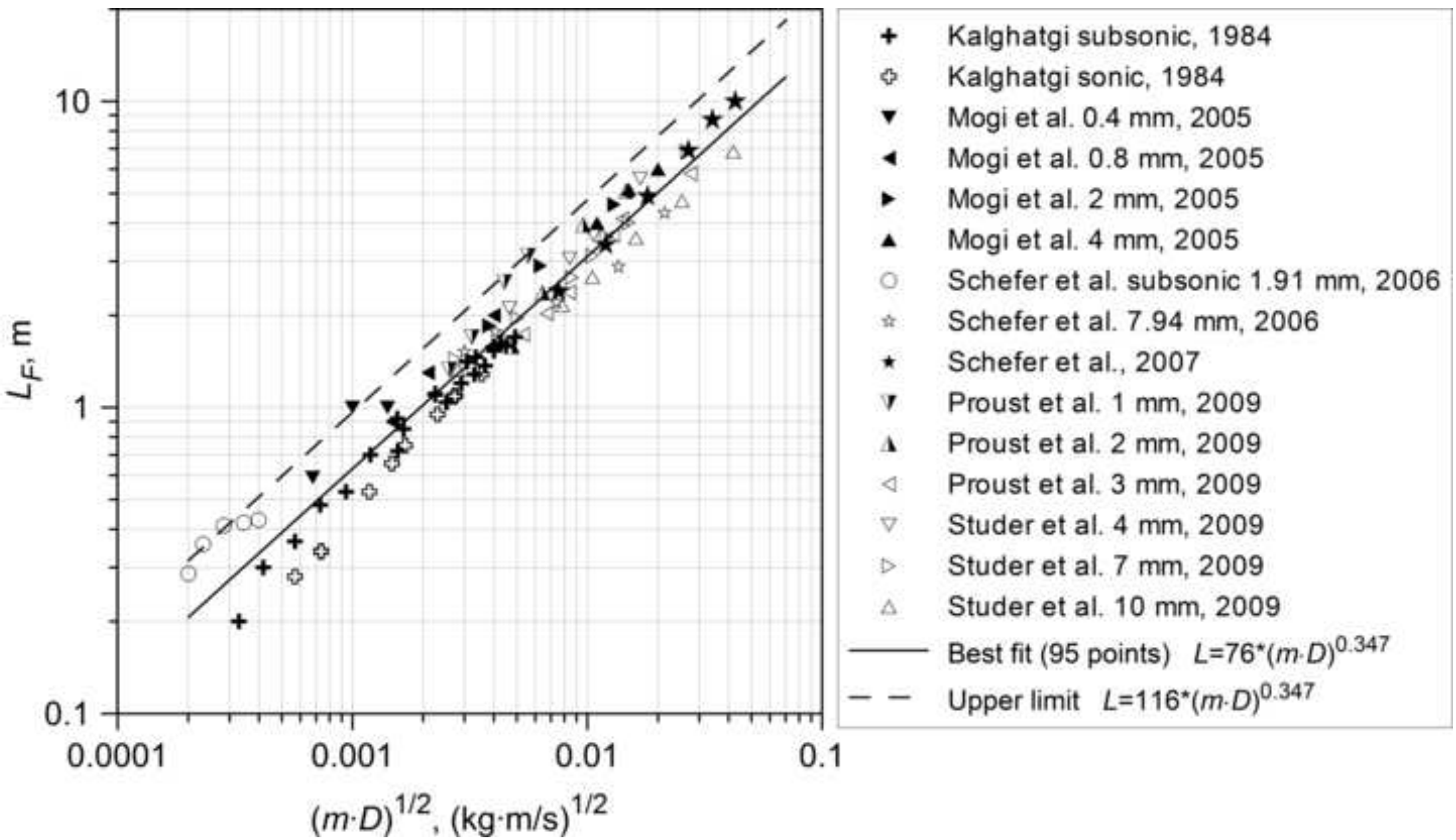

Figure 9
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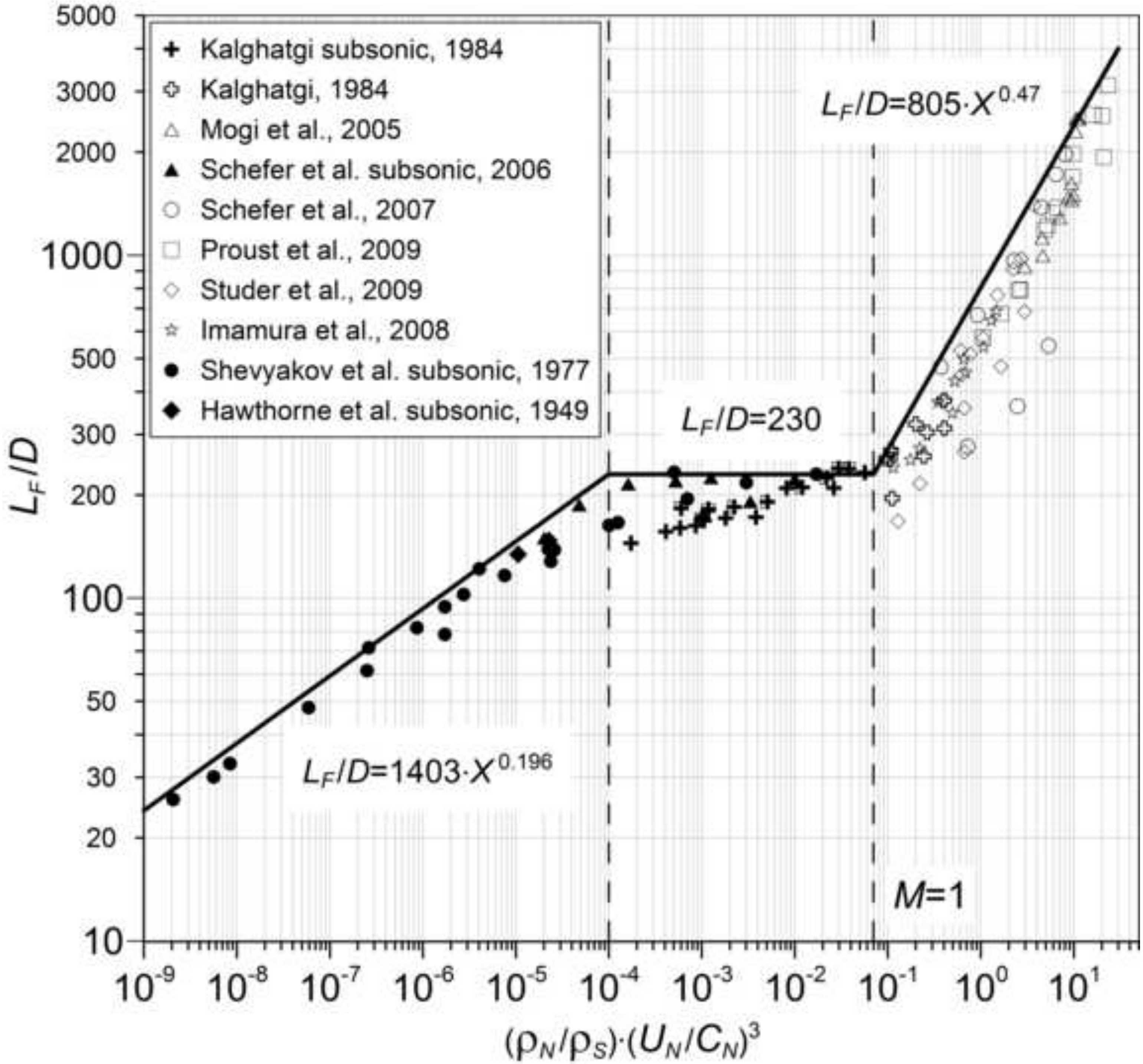

Figure 10
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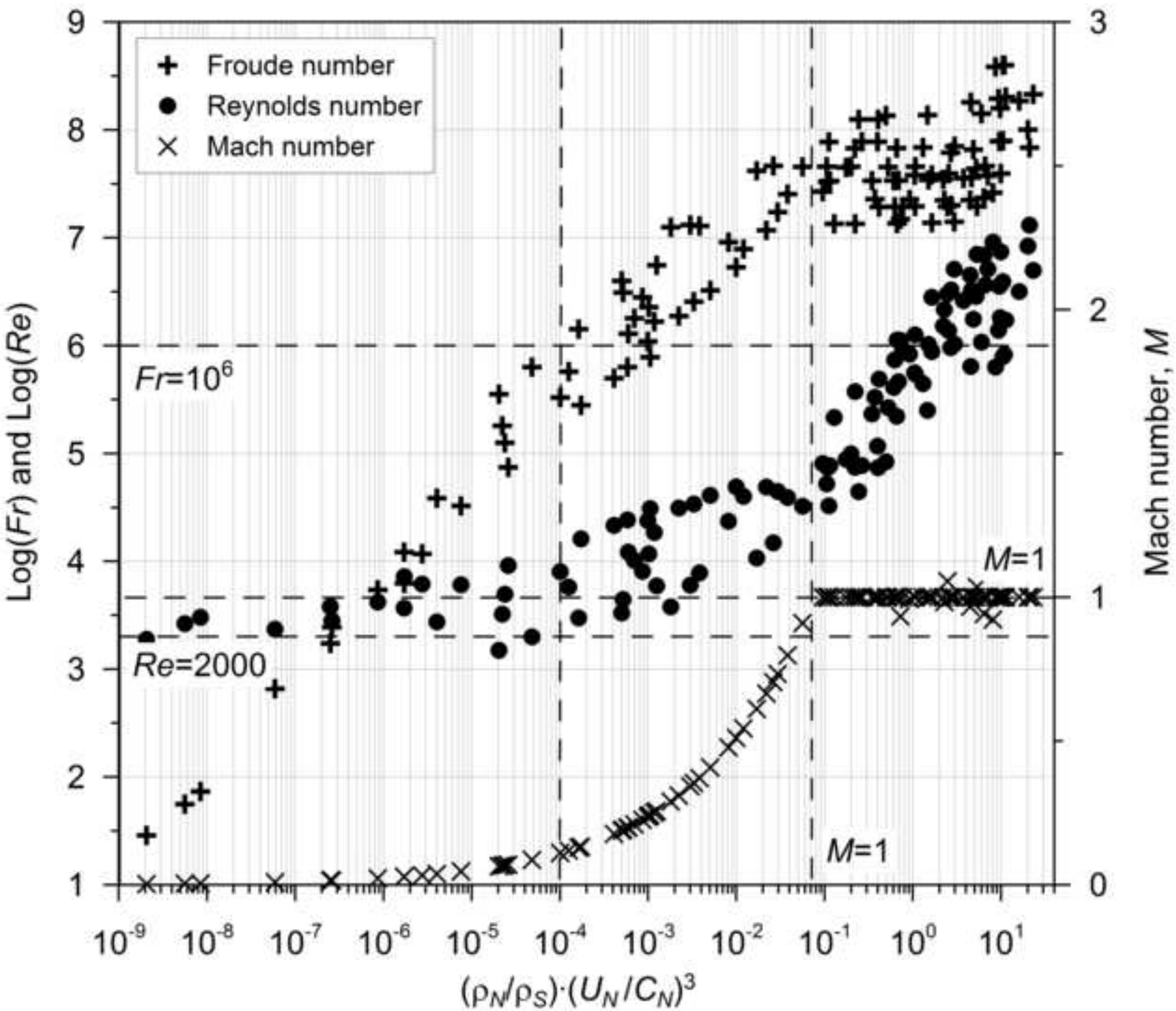

Figure 11
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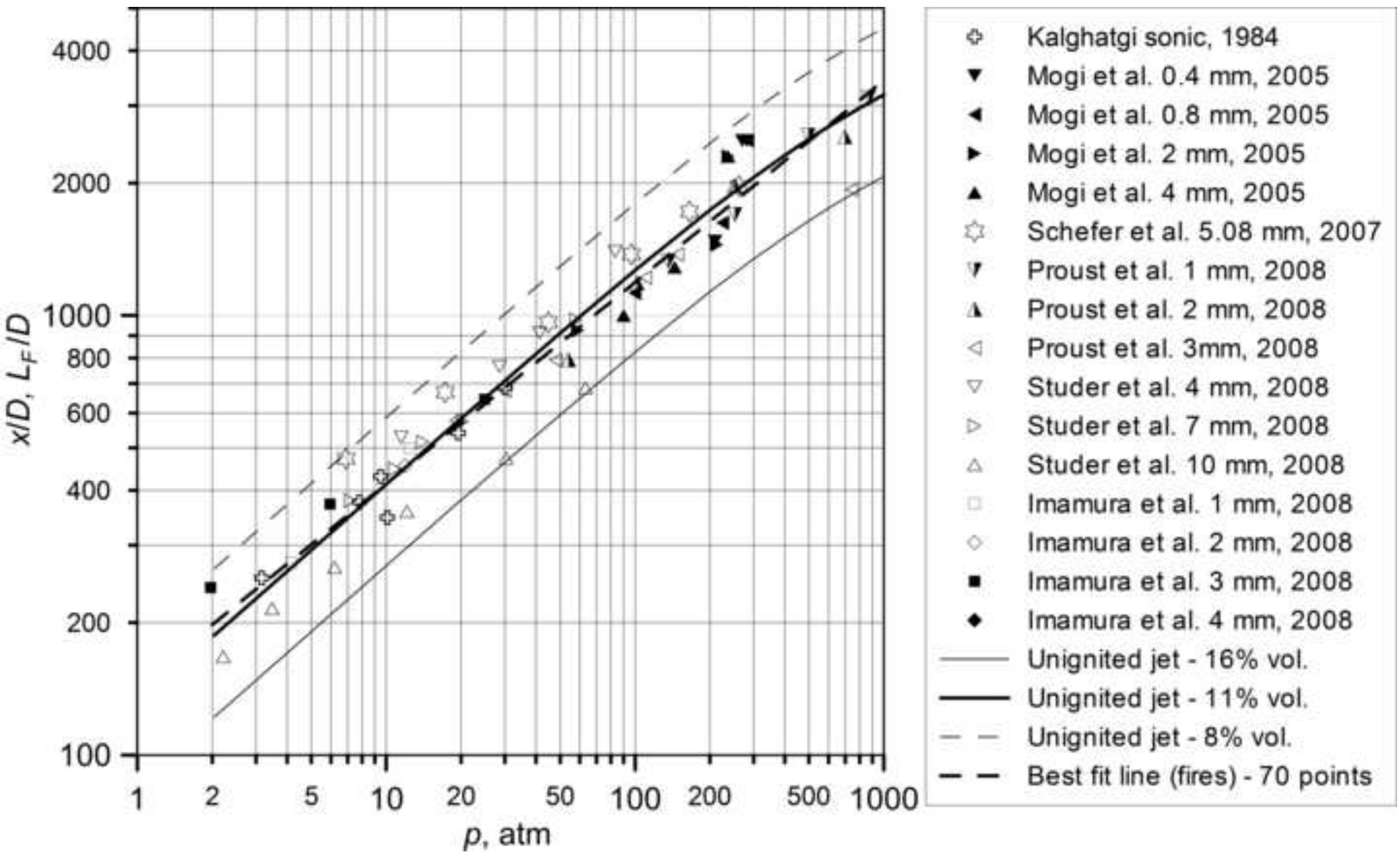

Figure 12
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